CHP Systems Analysis Methodology and Applications

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Energy Program
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Key Activities of CHP TAP

Market Opportunity Analysis:
Analyze CHP market opportunities in industrial, federal, institutional, and commercial sectors.

Education and Outreach:
Provide information on the energy and non-energy benefits and applications of CHP to state and local policy makers, regulators, energy end-users, trade associations, and others.

Technical Assistance:
Provide assistance to end-users and stakeholders to help them consider CHP, waste heat to power, and/or district energy with CHP in their facility and to help them navigate the project development process from initial CHP screening to installation.

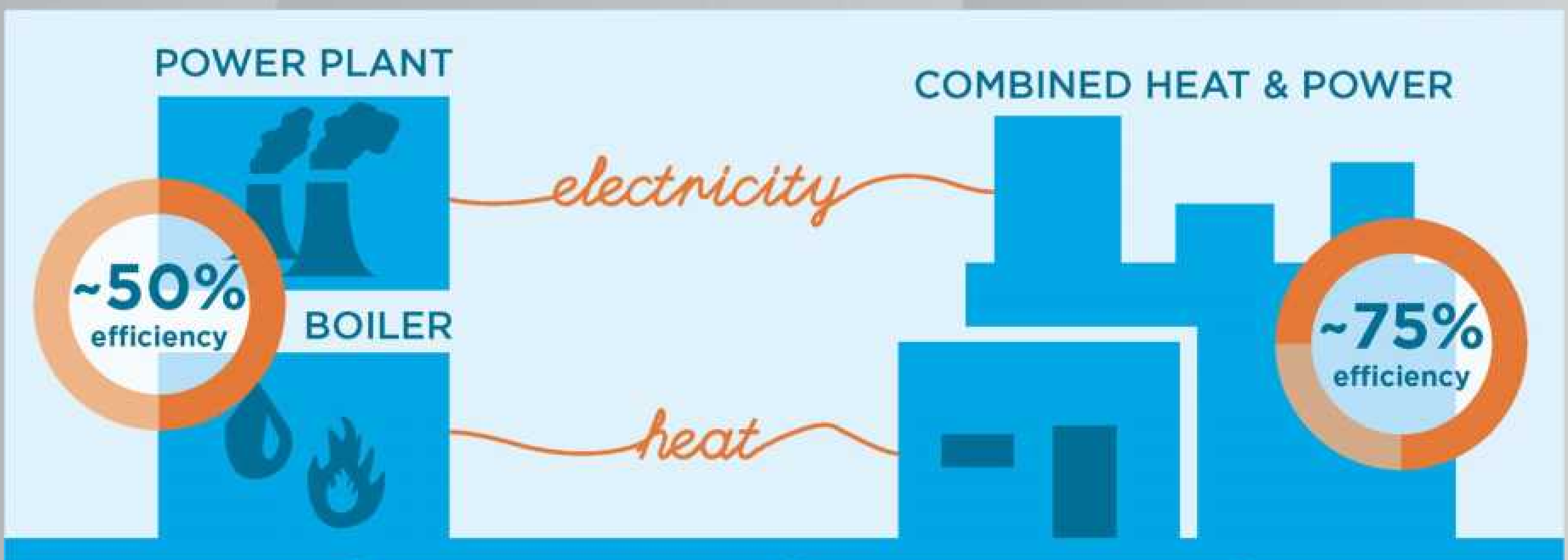
Outline of Presentation

- Overview of CHP & benefits
- CHP technology & equipment
- Building codes
- Project development process & CHP Technical Assistance Partnership Services

Combined Heat and Power: A Key Part of Our Energy Future

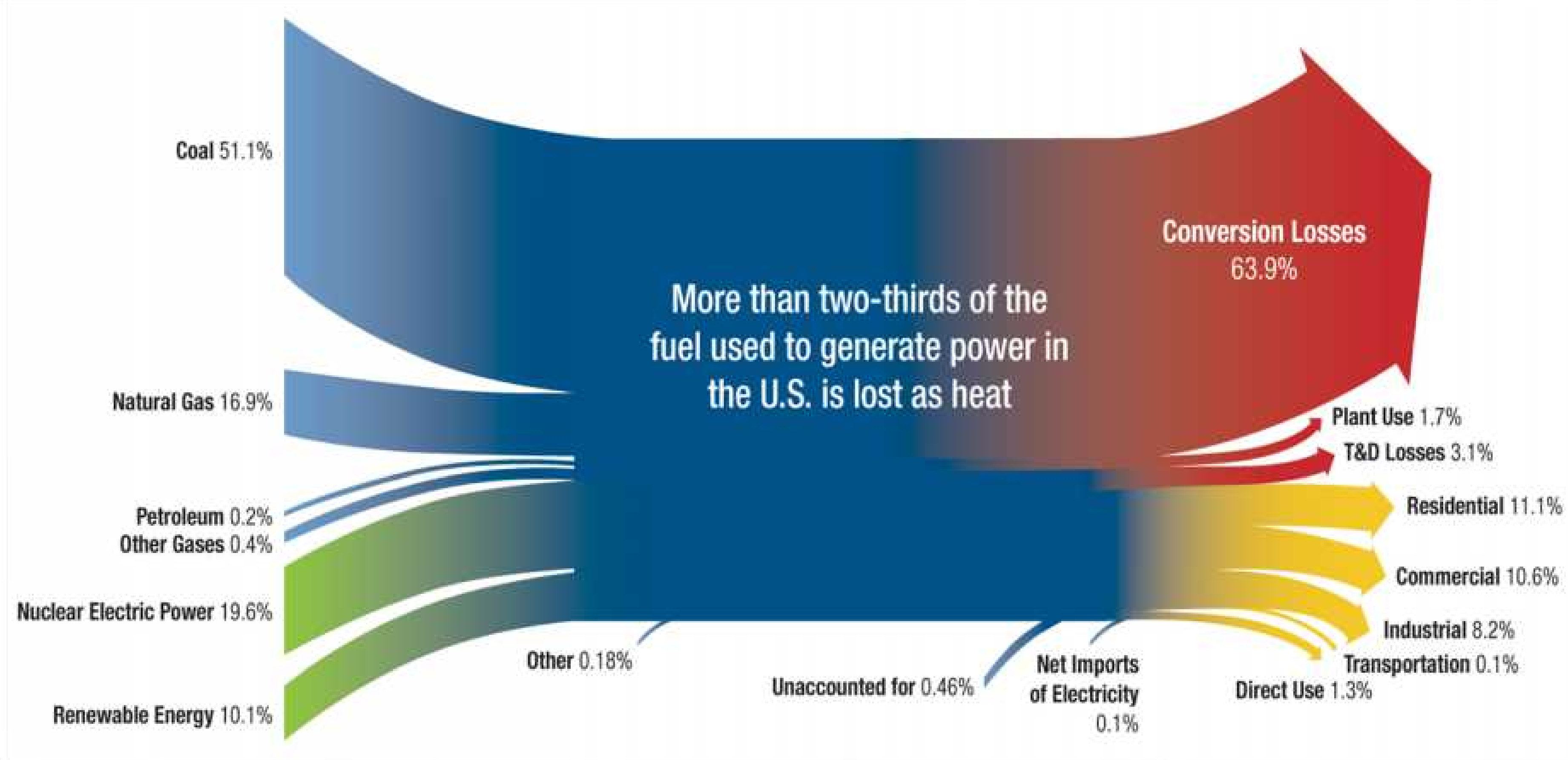
- Located at or near a building or facility
- Provides at least a portion of the electrical load
- Uses thermal energy for:
  - Space heating/cooling
  - Process heating/cooling
  - Dehumidification

CHP provides efficient, clean, reliable, affordable energy – today and for the future.



Combined Heat and Power: A Key Part of Our Energy Future

Over two-thirds of the fuel used to generate power in the U.S. is lost as heat



Benefits of Combined Heat and Power

- CHP is *more efficient* than separate generation of electricity and heat
- Higher efficiency translates to *lower operating cost*, (but requires capital investment)
- Higher efficiency *reduces emissions of all pollutants*
- CHP can also *increase energy reliability and enhance power quality*
- On-site electric generation *reduces grid congestion and avoids distribution costs*

National Goal: ***Additional*** 40 GW of CHP

Achieving this goal would:

- Increase total CHP capacity in the U.S. by **50%**
- Save energy users **$10 billion a year** compared to current energy use
- Save **one quadrillion Btus** (Quad) of energy — equivalent to 1% of all energy use in the U.S.
- Reduce emissions by **150 million metric tons of CO_2 annually** — equivalent to the emissions from over 25 million cars
- Result in **$40-$80 billion in new capital investment in manufacturing** and other U.S. facilities over the next decade

Source: DOE/EPA CHP: A Clean Energy Solution August 2012, www1.eere.energy.gov/manufacturing/distributedenergy/pdfs/chp_clean_energy_solution.pdf

CHP Projects Nationwide

>4,400 CHP sites (2014)

82,700 MW – installed capacity (2014)

Saves 1.8 quads of fuel each year

Avoids 241 M metric tons of CO_2 each year

86% of capacity – industrial

69% of capacity – natural gas fired

Source: DOE CHP Installation Database (U.S. installations as of Dec. 31, 2014)

Attractive CHP Markets




Industrial
Chemical manufacturing
Ethanol
Food processing
Natural gas pipelines
Petrochemicals
Pharmaceuticals
Pulp and paper
Refining
Rubber and plastics

Commercial
Data centers
Hotels and casinos
Multi-family housing
Laundries
Apartments
Office buildings
Refrigerated warehouses
Restaurants
Supermarkets
Green buildings

Institutional
Hospitals
Schools (K-12)
Universities & colleges
Wastewater treatment
Residential
Correctional Facilities

Agricultural
Dairies
Wood waste (biomass)
Animal feeding operations

Prime Mover: Reciprocating Engines

- Size range: 10 kW to 18 MW
- Characteristics:
  - Thermal can produce hot water, low- pressure steam, and chilled water (through absorption chiller)
  - High part-load operation efficiency
  - Fast start-up
  - Minimal auxiliary power requirements for black start
- Example applications:
  - Food processing, office buildings, multifamily housing, nursing homes, hospitals, schools, universities, wastewater treatment

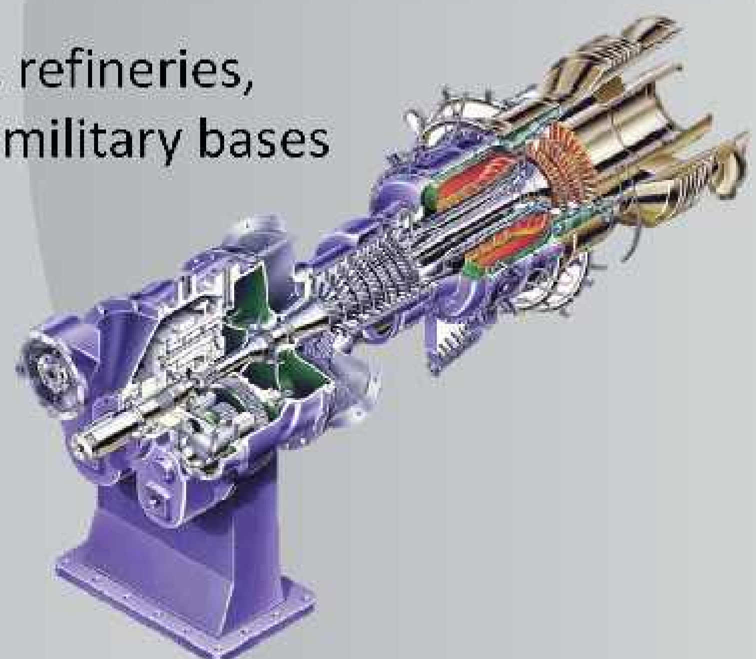
Source: DOE/EPA Catalog of CHP Technologies

Reciprocating Engine Characteristics

Cost & Performance Characteristics[14]	System				
	1	2	3	4	5
Baseload Electric Capacity (kW)	100	633	1,121	3,326	9,341
Total Installed Cost in 2013 ($/kW)[15]	$2,900	$2,837	$2,366	$1,801	$1,433
Electrical Heat Rate (Btu/kWh), HHV[16]	12,637	9,896	9,264	8,454	8,207
Electrical Efficiency (%), HHV	27.0%	34.5%	36.8%	40.4%	41.6%
Engine Speed (rpm)	2,500[17]	1,800	1,800	1,500[18]	720
Fuel Input (MMBtu/hr), HHV	1.26	6.26	10.38	28.12	76.66
Required Fuel Gas Pressure (psig)	0.4-1.0	> 1.16	> 1.74	> 1.74	75
CHP Characteristics					
Exhaust Flow (1000 lb/hr)	1.2	7.89	13.68	40.17	120
Exhaust Temperature (Fahrenheit)	1,200	941	797	721	663
Heat Recovered from Exhaust (MMBtu/hr)	0.21	1.48	2	5.03	10
Heat Recovered from Cooling Jacket (MMBtu/hr)	0.46	0.72	1.29	1.63	4.27
Heat Recovered from Lube System (MMBtu/hr)	Incl.	0.27	0.44	1.12	5.0
Heat Recovered from Intercooler (MMBtu/hr)	n/a	0.31	0.59	2.89	7.54
Total Heat Recovered (MMBtu/hr)	0.67	2.78	4.32	10.67	26.81
Total Heat Recovered (kW)	196	815	1,266	3,126	7857

Prime Mover: Combustion Gas Turbine

- Size range: 500 kW to 300 MW
- Characteristics:
  - Produces high-quality, high-temperature thermal that can include high-pressure steam for industrial processes; and chilled water (with absorption chiller)
  - Efficiency at part load can be substantially less than at full load
- Example applications:
  - Hospitals, universities, chemical plants, refineries, food processing, paper manufacturing, military bases



Source: DOE/EPA Catalog of CHP Technologies

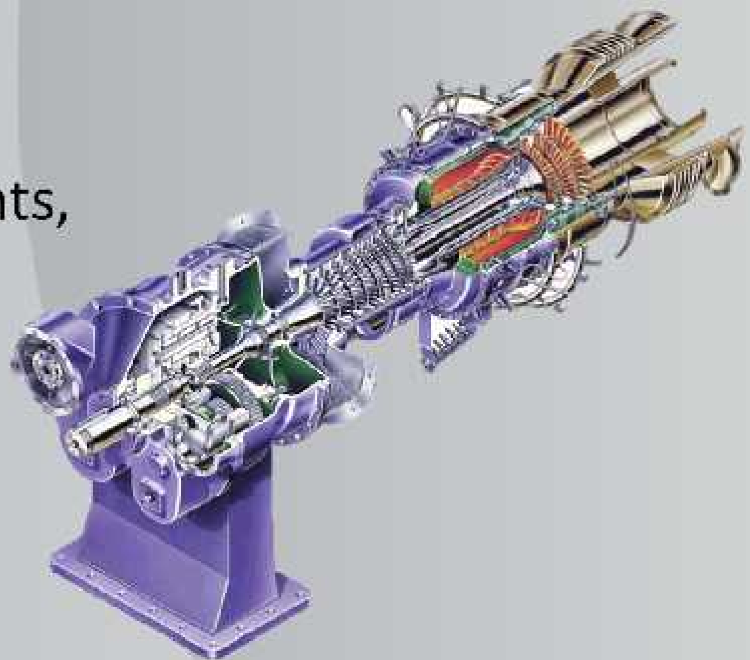
Gas Turbine Characteristics

Cost & Performance Characteristics	SYSTEM				
	1	2	3	4	5
Exhaust Flow (1,000 lb/hr)	149.2	211.6	334	536	1047
GT Exhaust Temperature (Fahrenheit)	838	916	913	874	861
HRSG Exhaust Temperature (Fahrenheit)	336	303	322	326	300
Steam Output (MMBtu/hr)	19.66	34.44	52.36	77.82	138.72
Steam Output (1,000 lbs/hr)	19.65	34.42	52.32	77.77	138.64
Steam Output (kW equivalent)	5,760	10,092	15,340	22,801	40,645
Total CHP Efficiency (%) HHV	65.7%	70.4%	69.5%	70.5%	68.8%
Power/Heat Ratio	0.57	0.7	0.65	0.89	1.09
Net Heat Rate (Btu/kWh)	6,810	5,689	5,905	5,481	5,590
Effective Electrical Efficiency (%)	50%	60%	58%	62%	61%
Thermal Output as Fraction of Fuel Input	0.42	0.41	0.42	0.37	0.33
Electric Output as Fraction of Fuel Input	0.24	0.29	0.27	0.33	0.36

Source: ICF vendor-supplied data

Heat Recovery Steam Generator (HRSG)

- Reduces cost of electricity
  - Up to 50% output without additional fuel consumption
- Reduces environmental footprint
  - Emissions reduced by at least 30% per MWh produced
- Increases flexibility and reliability
  - Hospitals, universities, chemical plants, refineries, food processing, paper manufacturing, military bases

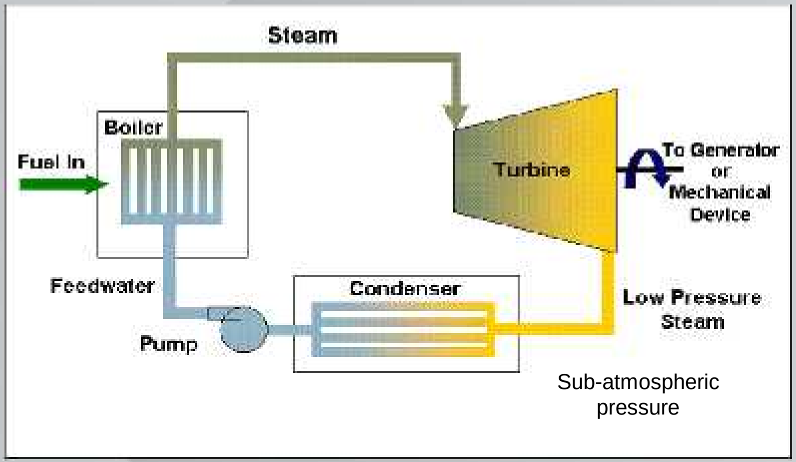


Source: DOE/EPA Catalog of CHP Technologies

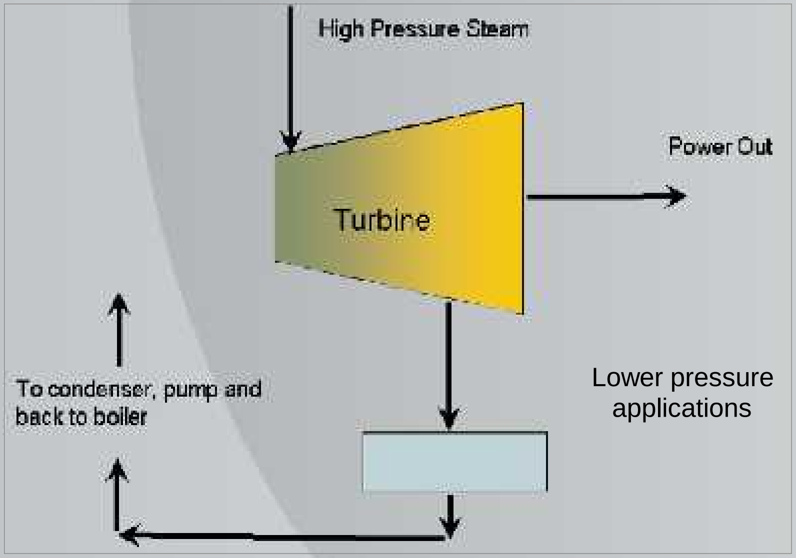
Steam Turbines:

One of the oldest prime mover technologies still in use

- Condensing turbines:
  - Industrial waste heat streams can be used to produce steam
  - Excess steam can be used to produce electrical energy



- Backpressure turbine:
  - Produces electrical energy at locations where steam pressure is reduced with a PRV



Prime Mover: Microturbines

- Size range: 30 kW to 330 kW
- Characteristics:
  - Thermal can produce hot water, steam, and chilled water
  - Compact size and light weight, brought on line quickly
  - Inverter-based generation can improve power quality
  - Usually below 200 kW unless multiple units utilized
  - Recuperator typical
- Example applications:
  - Multifamily housing, hotels, nursing homes, wastewater treatment, gas and oil production

Source: DOE/EPA Catalog of CHP Technologies

Microturbine Characteristics

Microturbine Characteristics	SYSTEM					
	1	2	3	4	5	6
Nominal Electricity Capacity (kW)	30	65	200	250	333	1000
Compressor Parasitic Power (kW)	2	4	10	10	13	50
Net Electricity Capacity (kW)	28	61	190	240	320	950
Fuel Input (MMBtu/hr)	0.434	0.876	2.431	3.139	3.894	12.155
Required Fuel Gas Pressure (psig)	55-60	75-80	75-80	80-140	90-140	75-80
Electric Heat Rate (Btu/kWh), LHV [2]	13,995	12,966	11,553	11,809	10,987	11,553
Electric Efficiency (%), LHV [3]	24.4%	26.3%	29.5%	28.9%	31.1%	29.5%
Electric Heat Rate (Btu/kWh), HHV	15,535	14,393	12,824	13,110	12,198	12,824
Electric Efficiency (%), HHV	21.9%	23.7%	26.6%	26.0%	28.0%	26.6%
CHP Characteristics						
Exhaust Flow (lbs/sec)	0.68	1.13	2.93	4.7	5.3	14.7
Exhaust Temperature (°F)	530	592	535	493	512	535
Heat Exchanger Exhaust Temperature (°F)	190	190	200	190	190	200
Heat Output (MMBtu/hr)	0.21	0.41	0.88	1.28	1.54	4.43

Source: ICF vendor-supplied data

Prime Mover: Fuel Cells

- Size range: 3 kW to 2 MW
- Characteristics:
  - Relatively high electrical efficiencies due to electrochemical process
  - Uses hydrogen as the input fuel
  - Relatively low emissions without controls due to absence of combustion process
  - Inverter-based generation can improve power quality
  - Relatively high installed cost, ~$5k/kW
- Example applications:
  - Data centers, hotels, office buildings, wastewater treatment

Source: DOE/EPA Catalog of CHP Technologies

Fuel Cell Characteristics

	PEMFC	PAFC	MCFC	SOFC
Type of Electrolyte	H^+ ions (with anions bound in polymer membrane)	H^+ ions (H_3PO_4 solutions)	$CO_3^=$ ions (typically, molten $LiKaCO_3$ eutectics)	$O^=$ ions (Stabilized ceramic matrix with free oxide ions)
Common Electrolyte	Solid polymer membrane	Liquid phosphoric acid in a lithium aluminum oxide matrix	Solution of lithium, sodium, and/or potassium carbonates soaked in a ceramic matrix	Solid ceramic, Yttria stabilized zirconia (YSZ)
Typical construction	Plastic, metal or carbon	Carbon, porous ceramics	High temp metals, porous ceramic	Ceramic, high temp metals
Internal reforming	No	No	Yes, good temp match	Yes, good temp match
Oxidant	Air to O_2	Air to Enriched Air	Air	Air
Operational Temperature	150- 180°F (65-85°C)	302-392°F (150-200°C)	1112-1292°F (600-700°C)	1202-1832°F (700-1000°C)
DG System Level Efficiency (% HHV)	25 to 35%	35 to 45%	40 to 50%	45 to 55%
Primary Contaminate Sensitivities	CO, Sulfur, and NH3	CO < 1%, Sulfur	Sulfur	Sulfur

Source: U.S. DOE Fuel Cell Technologies Program

Fuel Cell Characteristics

Performance Characteristics	System 1	System 2	System 3	System 4	System 5
Fuel Cell Type	PEMFC	SOFC	MCFC	PAFC	MCFC
Nominal Electricity Capacity (kW)	0.7	1.5	300	400	1,400
Net Electrical Efficiency (%), HHV)	35.3%	54.4%	47%	34.3%	42.5%
Fuel Input (MMBtu/hr), HHV	0.0068	0.0094	2.2	4.0	11.2
Total CHP Efficiency (%), HHV	86%	74%	82%	81%	82%
Power to Heat Ratio	0.70	2.78	1.34	0.73	1.08
Net Heat Rate (Btu/kWh), HHV	9,666	6,272	7,260	9,948	8,028
Exhaust Temperature (°F)	NA	NA	700	NA	700
Available Heat (MMBtu/hr)	NA	NA	0.78 (to 120°F)	0.88 (to 140°F)	3.73 (to 120°F)
Sound (dBA)	NA	47 (at 3 feet)	72 (at 10 feet)	65 (at 33 feet)	72 (at 10 feet)

NA = not available or not applicable
Source: ICF, specific product specification sheets

Approximating System Costs

Installed and O&M Cost Estimates:
CHP Prime Movers with Heat Recovery for Standard Installations

	Installed Costs	O & M Costs
Reciprocating Engines	$1,000 to $1,800 per kW	$0.010 to .015 per kWh
Gas Turbines	$800 to $1,500 per kW	$0.005 to $0.008 per kWh
Microturbines	$1,000 to $2,000 per kW	$0.010 to $0.15 per kWh

Absorption chillers: $500 to $1,000/RT (dependent on size)

Thermal-to-Power Ratio (T/P) of Facility

Determine what prime mover to select

1. Determine Thermal Use			
a.	Sum the number of **Therms** utilized over the *last 12 months* of bills: **Total Therms**	**1,000,000**	Therms
b.	**Multiply** the **Total Therms** by 100,000 to get Thermal Btu: **Total Thermal Energy Purchased**	**$100 * 10^9$**	Btu
c.	**Multiply** the **Total Thermal Energy Purchased** by Boiler/Equipment Efficiency (typically 0.8) **Total Thermal Energy Delivered/Used**	**$80 * 10^9$**	Btu
2. Determine Electrical Use			
a.	Sum the number of **kWh** utilized over the *last 12 months* of bills: **Total kWh**	**16,000,000**	kWh
b.	**Multiply** the **Total kWh** by 3413 to get Btu **Total Electric**	**$55 * 10^9$**	Btu
3. Determine T/P Ratio			
	Divide Total Thermal *(Btu)* by **Total Electric** *(Btu)*: **T/P Ratio**	**1.46**	

If T/P =	
0.5 to 1.5	Consider *engines*
1 to10	Consider ***gas turbines***
3 to 20	Consider ***steam turbines***

Sizing a Combined Heat and Power System

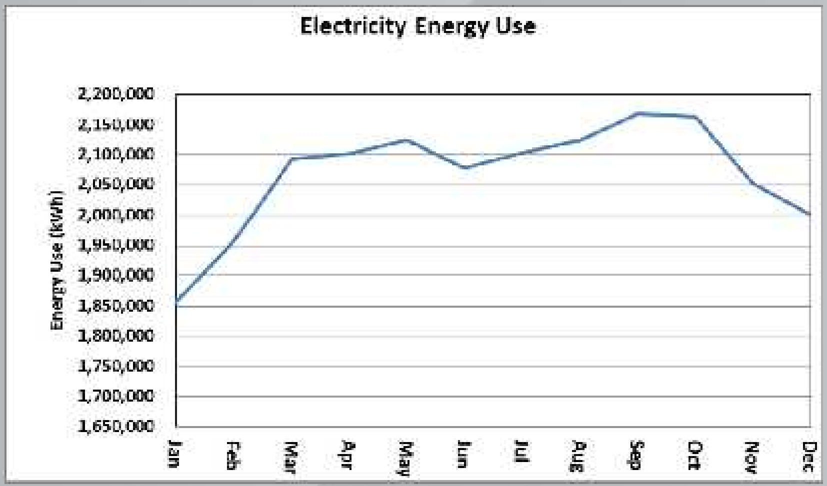
- Usually size for the base thermal load (which provides the highest efficiency and longest operation).
- Many commercial and institutional buildings seem to size best at ≈ 60% to 65% of peak electric demand
- Digester gas: Often considered “free gas” – consider sizing for maximum electricity given available volume of digester gas (selling back to utility).

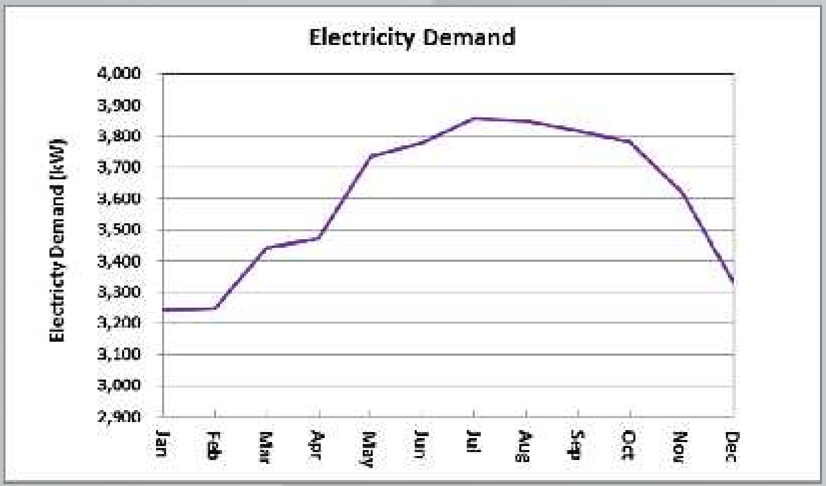
Chillers

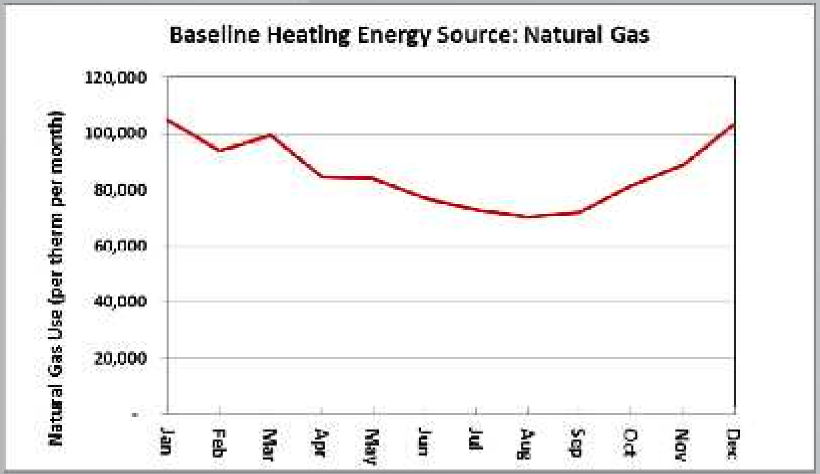
Absorption or *adsorption* chillers can be incorporated into the existing central mechanical plant operations in many ways:

- Waste heat application
- Part of a combined cooling, heat, and power (CCHP or tri-generation) application
- As a stand-alone gas-fired absorption chiller application
- Using renewable solar as the heat source for the refrigeration cycle

Chillers







- As much as $100,000/month in demand charges
- Summer months due to DX chillers
- Demand charge reduction possible with absorption chillers

Benefits of Chillers

- Reduce energy costs
- Stabilize risks associated with fluctuating energy costs
- Improve equipment reliability
- Reduce greenhouse gas emissions by up to 50% for the power generated
- Reduce grid congestion
- Reduce electrical demand charges
- Provide reliable power supply
- Use low global warming and ozone-safe natural refrigerants like R717 (NH_3) and R744 (CO_2), water and air, which are promoted through the LEED certification program, ASHRAE, EPA, DOE and GSA (CHP can be shown to offer 5-9 LEED points)

http://www.epa.gov/chp/treatment-chp-leedr-building-design-and-construction-new-construction-and-major-renovations

Meeting Cooling Requirements with Prime Mover Recoverable Heat

How much absorption cooling can be delivered from a prime mover?
How much electricity is offset by an absorption chiller?

Absorption Chillers (LiBr-H_20)

Capacity Range *(kW)*	**Single-Effect**	**Double-Effect**
COP	0.6-0.67	0.9-1.2
Heat Source		
Minimum Temperature, °F	180	350
Hot Water Flow Rate, lbs/h per RT	1,000	400
Steam Flow Rate, lbs/h per RT	18	10-11
Steam Pressure, psig	15	115-125
Integration w/ Waste Heat from:		
Reciprocating engines, RT/kW	0.22 - 0.28	0.3-0.4
Combustion turbines, RT/kW	0.28 - 0.33	0.4-0.5
Microturbines, RT/kW	0.33 - 0.45	NA
Average Electric Power Offset	0.6kW/RT	0.6kW/RT
Installed Cost *($/RT)*		
100 RT	1000	1200
500 RT	700	900
1,000 RT	650	850
2,000 RT	500	700
O&M Costs *($/RT/yr)*		
100 RT	30	30
500 RT- 2,000 RT	16-28	17-25

Codes that Apply to Using Natural Gas as a Fuel Source

- International Building Code (IBC) Chapter 27
- National Fire Protection Association (NFPA) 99 & 110
- National Electrical Code (NEC) Articles 700 & 701
- Center for Medicare and Medicaid Services (CMS) – define "low probability of failure"

International Building Code Ch. 27 Related Definitions

Emergency

- Voice communication
- Exit signs
- Egress illumination
- Doors on I-3
- Elevator car lighting
- Fire detection and alarms
- Fire pumps

Standby

- Smoke control
- Egress elevators/platforms
- Sliding doors
- Inflation for membrane structures
- Power & lighting for fire command

NFPA 99

6.4.1.1.7 Uses for Essential Electrical System

The generating equipment used shall be either reserved exclusively for such service or normally used for other purposes of peak demand control, internal voltage control, load relief for the external utility, or cogeneration.

NFPA 110.5.1
Energy Sources

5.1.1 The following sources* shall be permitted to be used for the emergency power supply (EPS):

- Liquid petroleum products at atmospheric pressure as specified in the appropriate ASTM standards and as recommended by the engine manufacturer
- Liquefied petroleum gas (liquid or vapor withdrawal) as specified in the appropriate ASTM standards and as recommended by the engine manufacturer
- Natural or synthetic gas

* Explanatory material can be found in Annex A of the NFPA codes

NEC Article 700 & 701
Emergency and Standby Fuel

“Article 700-12 (b)(3) Dual Supplies. Prime movers shall not be solely dependent on a public utility gas system for their fuel supply or municipal water supply for their cooling systems. Means shall be provided for automatically transferring from one fuel supply to another where dual fuel supplies are used.

Exception: Where acceptable to the authority having jurisdiction, the use of other than on-site fuels shall be permitted where there is a low probability of a simultaneous failure of both the off-site fuel delivery system and power from the outside electrical utility company.

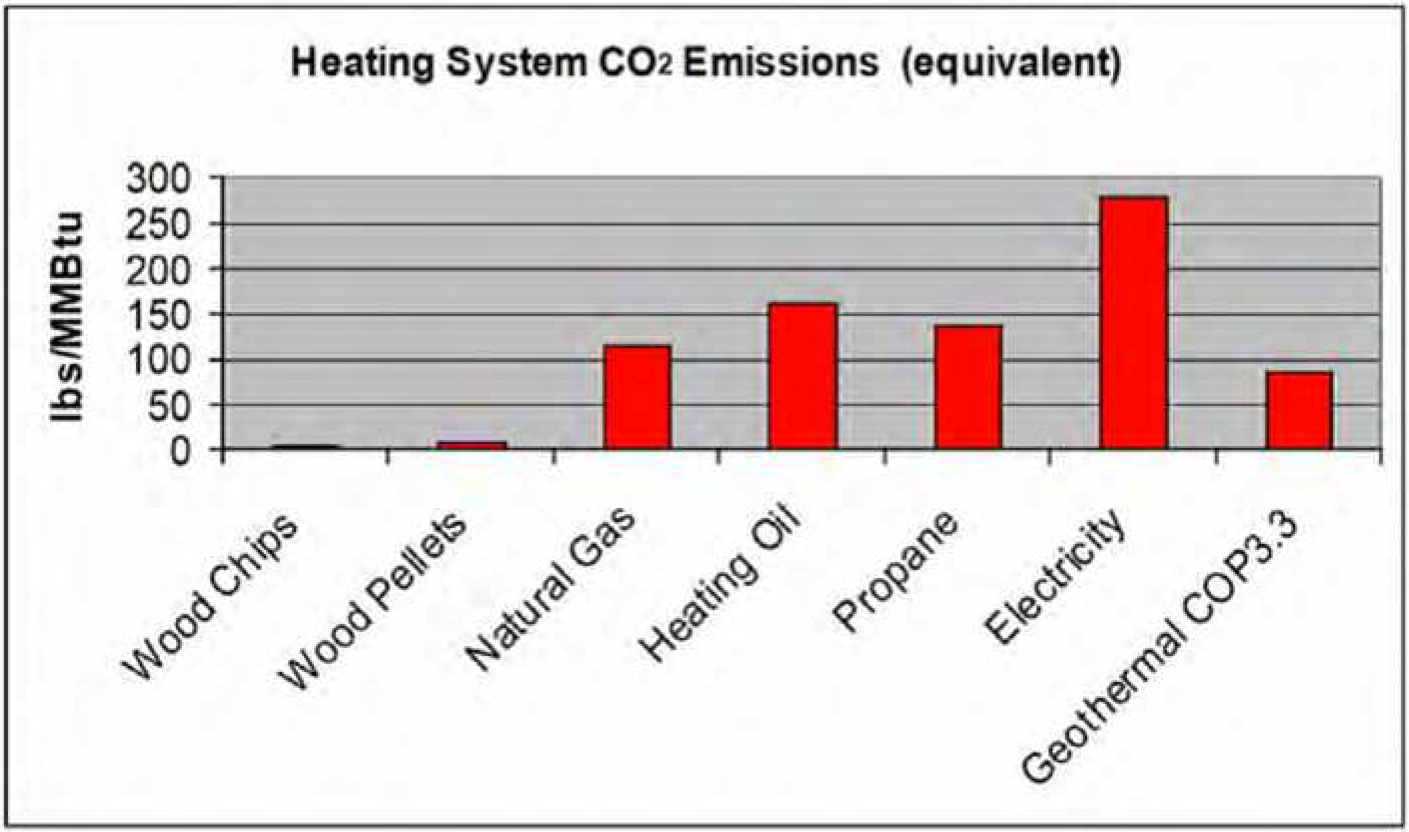
Center for Medicare & Medicaid Services (CMS) - Low Probability of Failure Defined

Natural Gas Generator Reliability Letter Requirements:

- Statement of reasonable reliability of the natural gas delivery
- Brief description that supports the statement regarding the reliability
- Statement that there is a low probability of natural gas interruption
- Brief description that supports the statement regarding the low probability of interruption
- Signature of technical personnel from the natural gas vendor

Sources: CMS 2009 presentation
http://chfs.ky.gov/NR/rdonlyres/4C745EDB-C9D8-4AA9-B111-38092C60EFB4/0/NaturalGasGenerators.pdf

Fuel Emissions



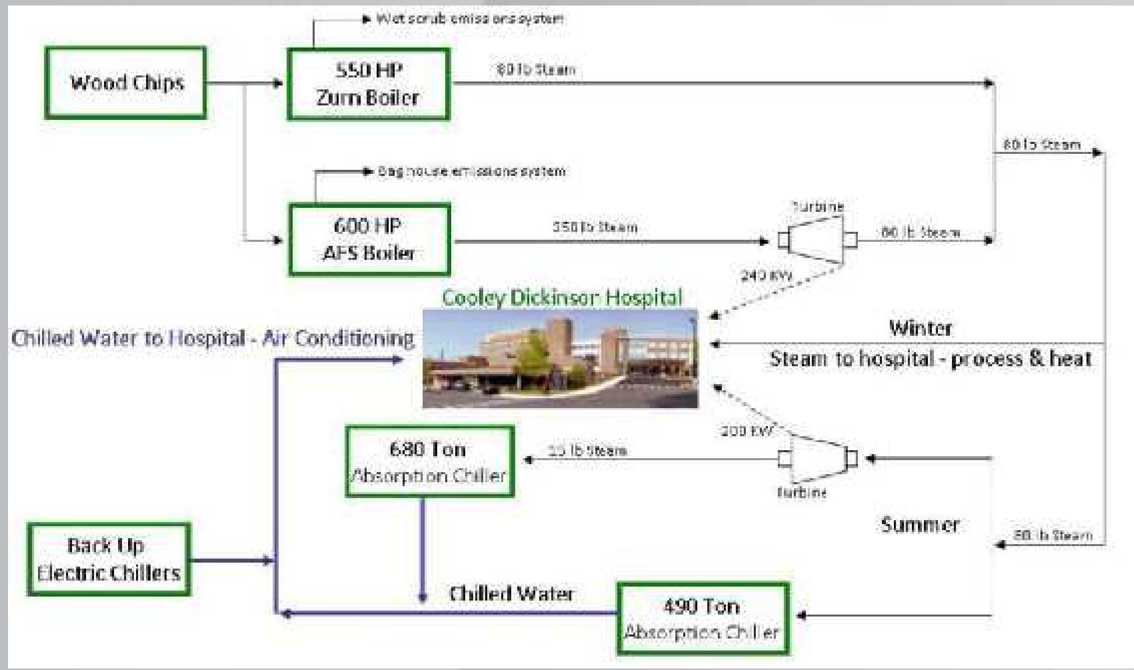
Source: Emission factors from www.nyserda.org and www.eia.doe.gov

Project Snapshot

Cooley Dickinson
Health Care
Northampton, MA

COOLEY DICKINSON
HEALTH CARE
MASSACHUSETTS GENERAL HOSPITAL AFFILIATE

Application/Industry: Hospitals
Capacity (MW): 500 KW
Prime Mover: Steam Turbine(s)
Fuel Type: Wood chips
Thermal Use: Heat and hot water
Installation Year: 2006



Testimonial: This SECOND biomass boiler eliminated the need to burn oil during annual maintenance downtime, reduces peak load by 17.5%, and produces approx. 2 million kWh electricity per year. The plant also has full utility company interconnectivity and operates in parallel with the electrical grid.

Source: http://www.northeastchptap.org/Data/Sites/5/documents/profiles/CooleyDickinsonCaseStudy.pdf

Steps to Solving the Problem

Determine

- Average electric demand
- Average price of purchased electricity
- Average natural gas consumption
- Average price of natural gas

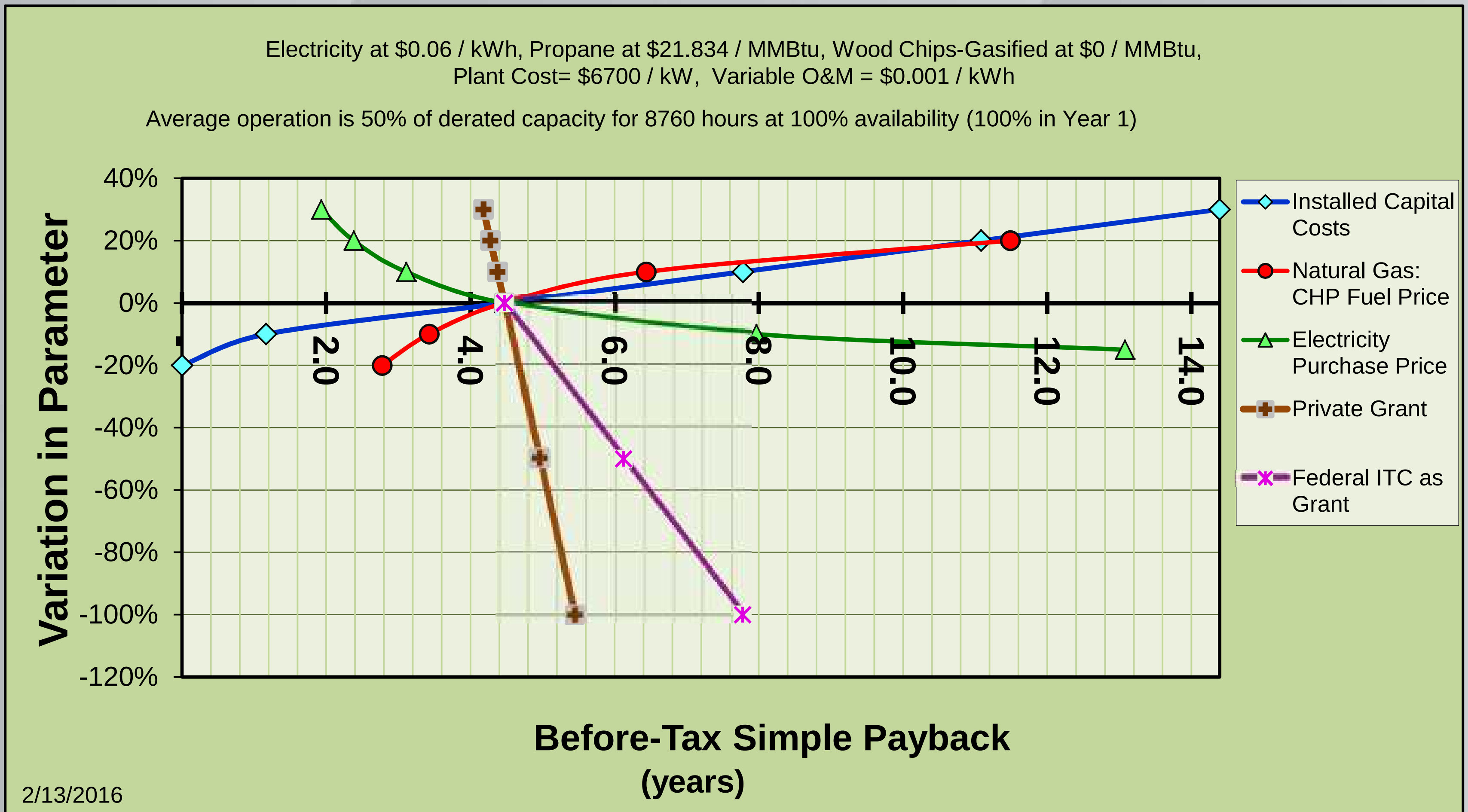
Then

- Size the CHP system: match electric loads and match thermal loads
- Determine energy savings, installed costs, and simple payback

Considerations of Example Problem

- What is this solution telling me?
- What other factors need to be considered?
  - Credit for backup generation
  - Carbon credits
  - Government grants
  - Tax credits (federal/state)
  - Utility Incentives
- Energy Price Sensitivity Analysis
  - 10% electric increase = 4.6 year payback
  - 20% electric increase = 3.6 year payback
  - 10% natural gas increase = 7.8 year payback
  - 20% natural gas increase = 10.4 year payback
  - 10% electric <u>AND</u> 10% natural gas increase = 5.4 year payback

Sample Sensitivity Diagram



Summary: When Looking at Your Facility, Consider…

- Is there a use for the CHP waste/recycled heat?
- Is a major rehab or thermal equipment change planned?
- Is there sufficient "spark spread"?
- Identify size and type of prime mover to meet thermal requirements (high efficiency).
- Will the selected configuration provide adequate waste heat levels for heating and/or cooling?
- Are there potential installation issues?
- Estimated installation costs?
- What do basic economics look like?

Is the application worth pursuing with a formal analysis?

Annual Energy Use Summary Sample

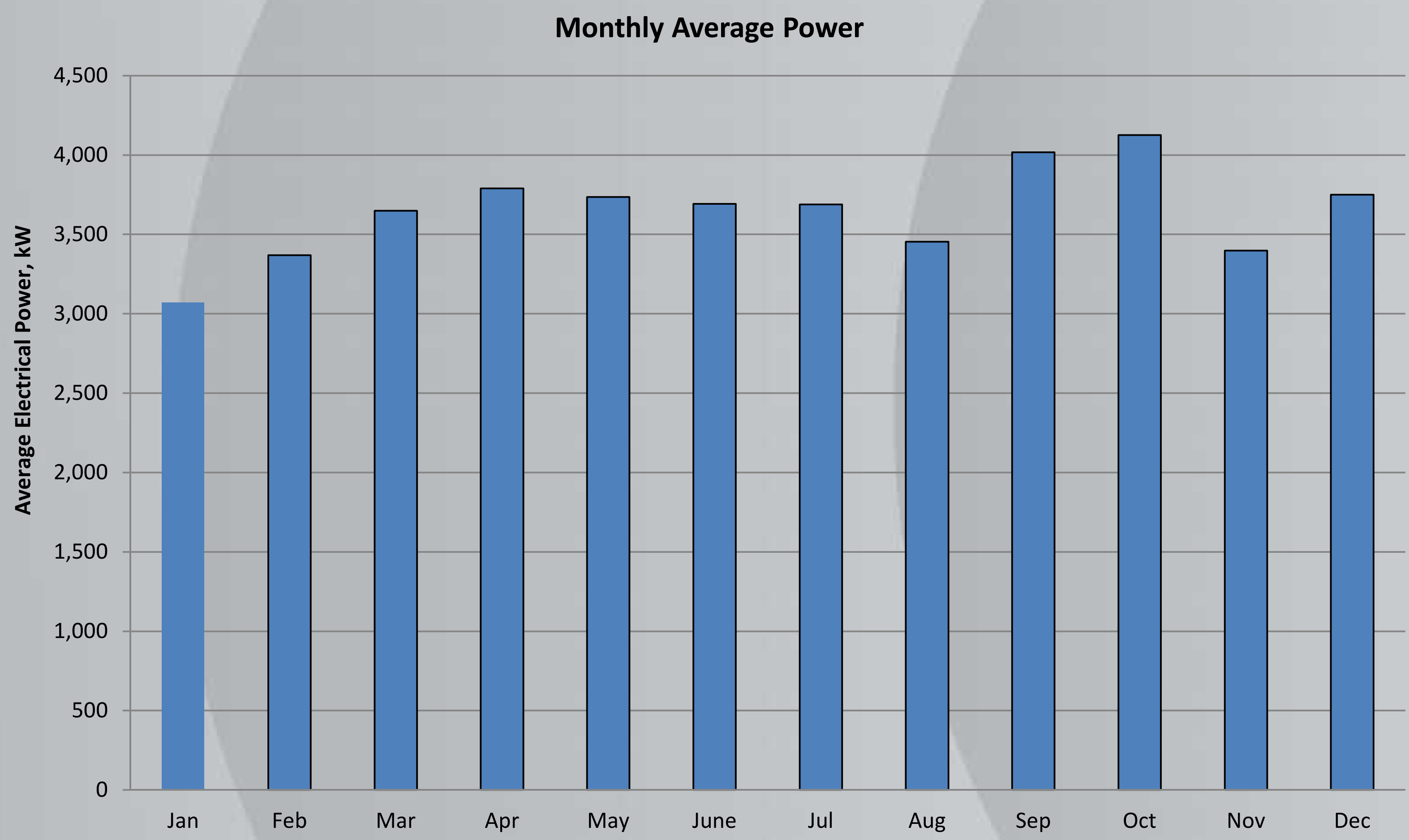
University							
Month	Electricity (kWh)	Electricity ($)	Electricity ($/kWh)	Natural Gas ($)	Natural Gas (therms)	Natural Gas ($/MMBtu)
Jan--15	2,286,840	$ 222,981	$ 0.098	$ 302,095	346,440	8.72
Feb	2,502,133	$ 243,245	$ 0.097	$ 237,035	271,830	8.72
Mar	2,714,835	$ 261,044	$ 0.096	$ 215,854	247,540	8.72
Apr	2,728,199	$ 263,761	$ 0.097	$ 184,201	211,240	8.72
May	2,779,795	$ 267,913	$ 0.096	$ 102,573	117,630	8.72
Jun	2,658,494	$ 255,518	$ 0.096	$ 49,064	118,600	**4.14**
Jul	2,744,758	$ 265,473	$ 0.097	$ 38,598	93,300	**4.14**
Aug--14	2,569,171	$ 239,037	$ 0.093	$ 31,797	76,860	**4.14**
Sep	2,892,800	$ 260,233	$ 0.090	$ 70,902	81,310	8.72
Oct	3,069,088	$ 271,540	$ 0.088	$ 99,050	113,590	8.72
Nov	2,446,105	$ 230,129	$ 0.094	$ 165,156	189,400	8.72
Dec	2,790,018	$ 262,327	$ 0.094	$ 283,574	325,200	8.72
	32,182,236	$3,043,201	$0.095	$1,779,899	**2,192,940**	$ 8.12

Costs of Natural Gas vs. Value of Electrical Energy

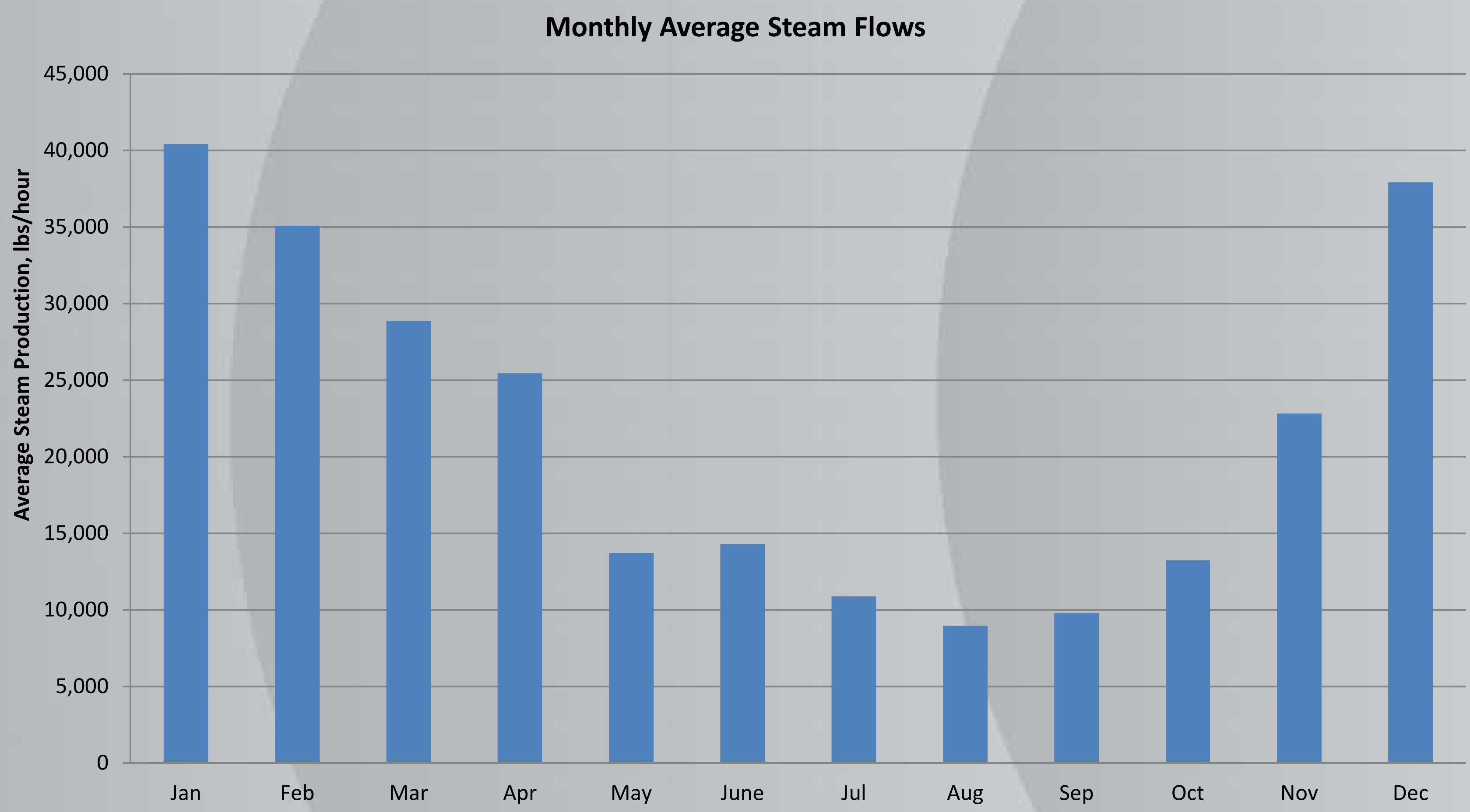
- \$0.095/kWh = \$27.8/MMBtu
- Natural gas at \$4.11/MMBtu = steam at \$4.11
  - (85% boiler efficiency) = \$4.83/MMBtu
- "Spark Spread" is \$22.97/MMBtu

Conclusion: Most of a CHP project's revenue stream comes from the production of electrical energy.

Monthly Average Power Electrical Load Profile



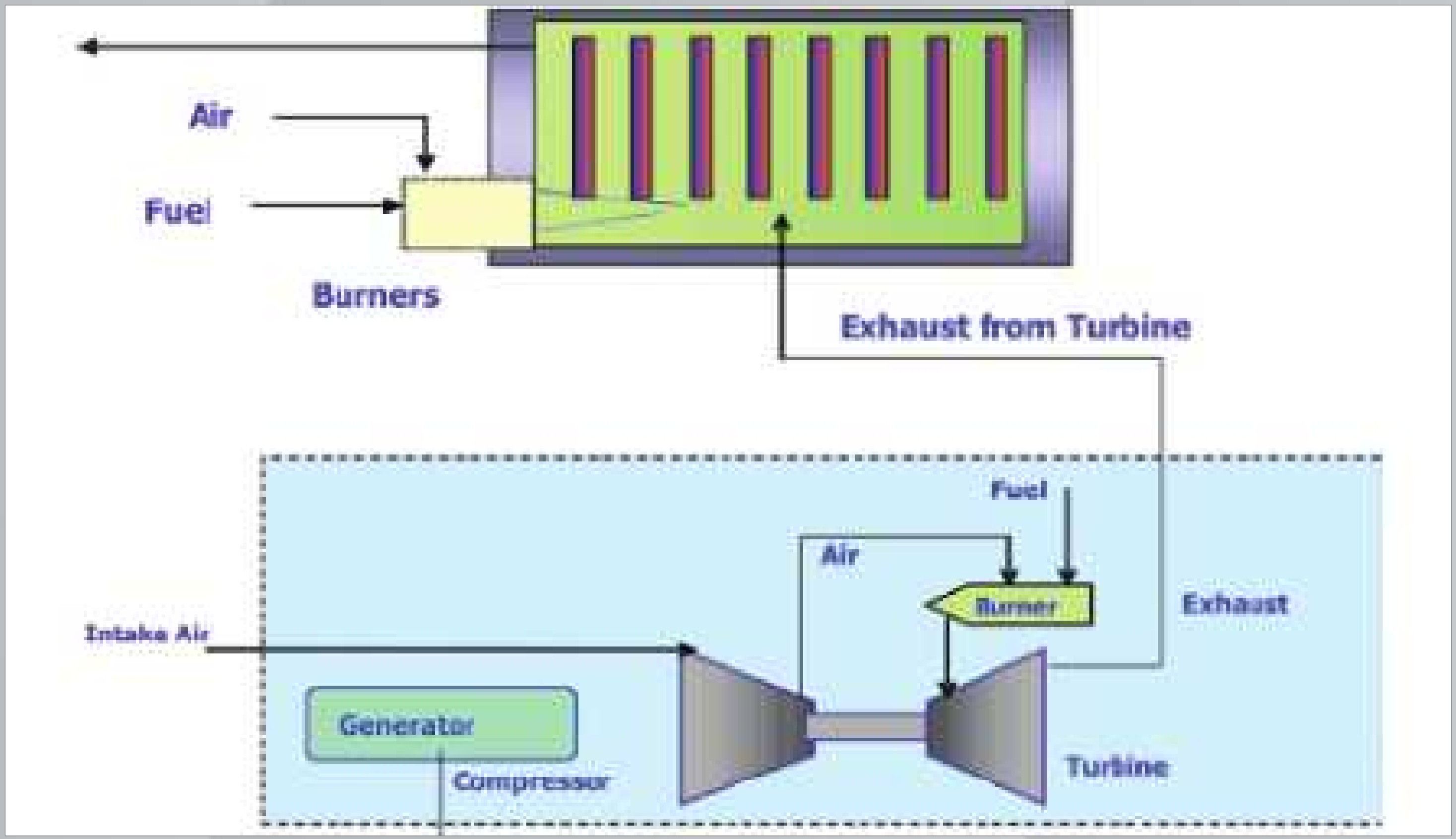
Monthly Average Steam Flows
Steam Flow Profile



CHP Prime Mover Selection

- Gas turbine with heat recovery steam generator – HRSG (to qualify as CHP)
  - Usually use natural gas as fuel, but can run on oil
  - Can add duct burner and even OSA firing capability to HRSG
- Backpressure, condensing, or condensing/extraction steam turbines
- Combined cycle project (Brayton plus Rankine cycles)
- Reciprocating engines
- Bottoming cycle power plants (organic Rankine for waste heat recovery). [Fouling, corrosion, erosion]

Gas Turbine with HRSG



Lower Heating Value (LHV)

- Gas turbines are rated at ISO conditions (59^{o}F at sea level, and 60% relative humidity)
- The firing rate (MMBtu/hour) and heat rate (Btu/kWh) are given in terms of lower heating value (LHV)
- Fuel (natural gas or oil) is sold on the basis of its higher heating value (HHV).

LHV, continued

- The LHV assumes that the latent heat of vaporization of water in the fuel and the reaction products is not recovered. It is useful when comparing fuels and turbine performance where condensation of the combustion products is impractical.
- Higher heating value (HHV) assumes that all of the water in a combustion process is in a liquid state after a combustion process.
- For natural gas, fuel consumption (HHV) $\cong$ fuel consumption (LHV)/0.9.

Turbine Selection/Coverage Charts

GAS TURBINE OVERVIEW

GAS TURBINE PACKAGES

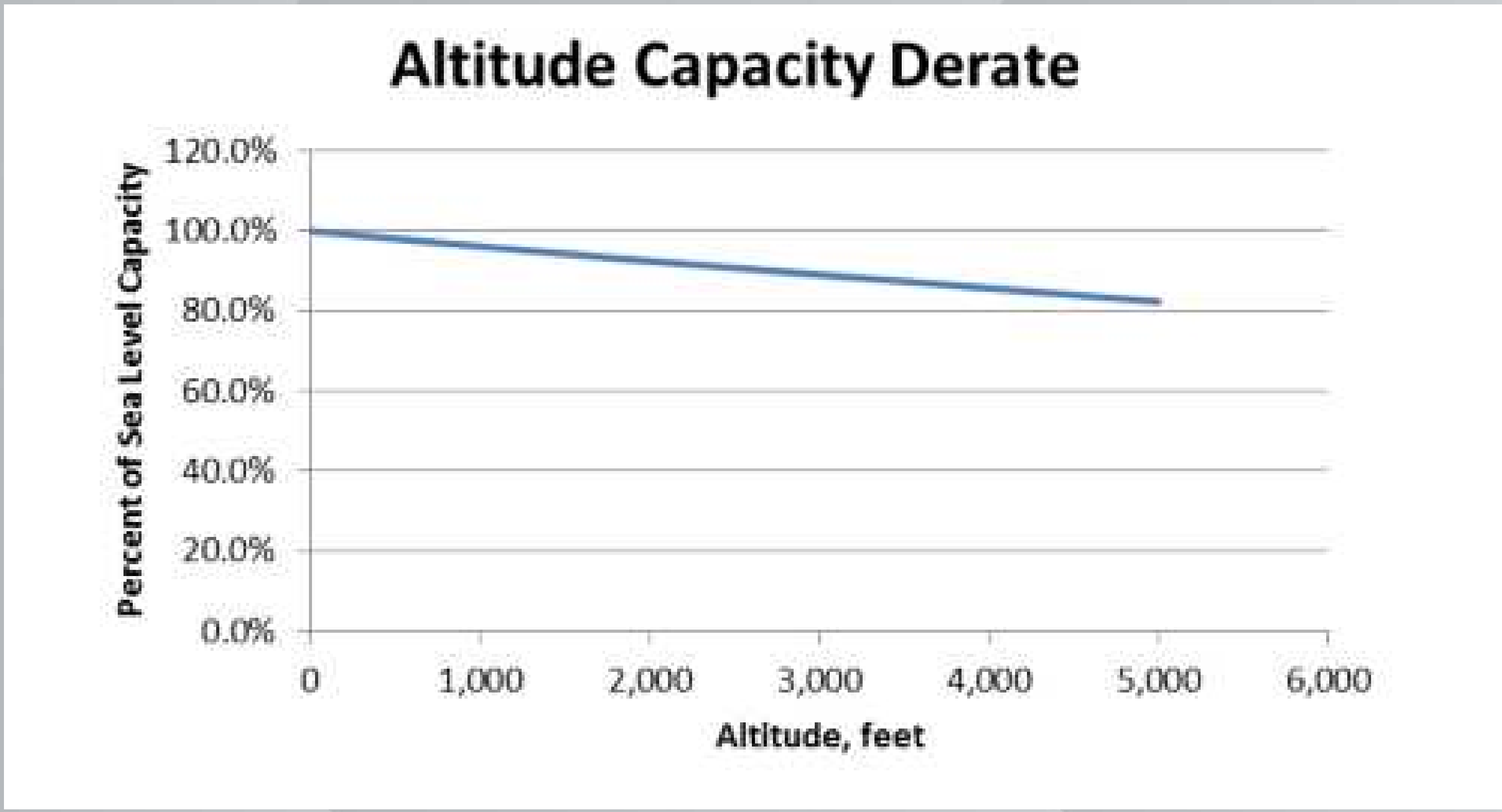
Solar builds complete turbomachinery packages that are ready to go to work no matter where the job might be worldwide. Solar designs and r
packages under various quality systems ensuring the highest reliability.

Compressor Sets

Power Range, hp (Thousands)	Shaft	1	5	10	1
Saturn 20	Two				
Centaur 40	Two				
Centaur 50	Two				
Taurus 60	Two				
Taurus 70	Two				
Mars 90	Two				

Gas Turbine Capacity

Rating for Altitude and Temperature



Source: U.S. EPA "Catalog of CHP Technologies," March 2015

Solar Turbines
A Caterpillar Company

CENTAUR 50
Gas Turbine Generator Set

Power Generation

General Specifications
Centaur® 50 Gas Turbine

Power Generation

Performance

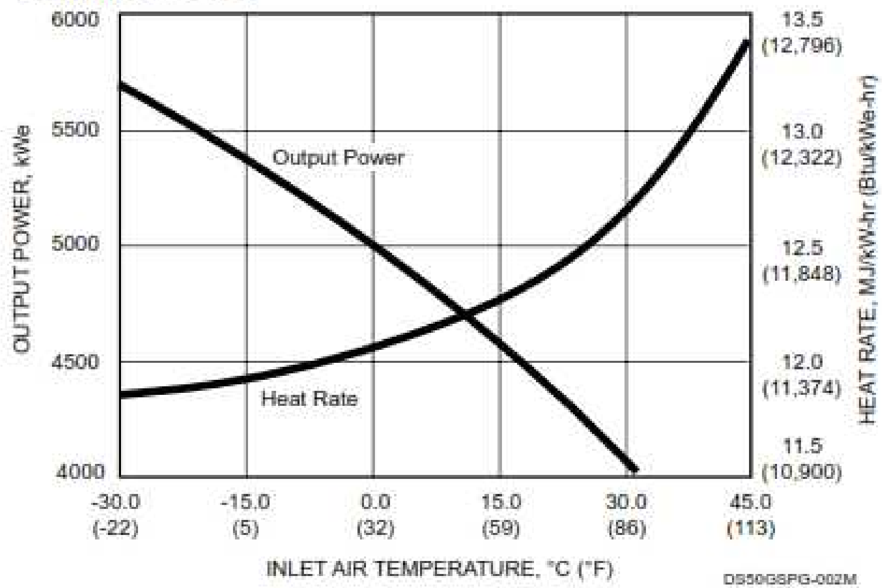
Output Power	4600 kWe
Heat Rate	12 270 kJ/kWe-hr (11,630 Btu/kWe-hr)
Exhaust Flow	68 680 kg/hr (151,410 lb/hr)
Exhaust Temp.	510°C (950°F)

Application Performance

Steam (Unfired)	11.5 tonnes/hr (25,280 lb/hr)
Steam (Fired) 1536°C (2800°F)	50.4 tonnes/hr (111,190 lb/hr)
Chilling (Absorp.)	9890 kW (2810 refrigeration tons)

Nominal rating – per ISO
At 15°C (59°F), sea level

Available Power



Site Altitude and Service Loads

Solar Centaur

Gas Turbine:	
KW Gross Output @ ISO Conditions:	4,600 kW
Site Ambient Temperature for Performance Analysis:	59 °F
Site Elevation for Performance Analysis:	3,209 feet
Site Ambient Relative Humidity for Performance Analysis:	60 %
Turbine Inlet Pressure Loss:	4.0 "H2O
Turbine Outlet Pressure Loss:	10.0 "H2O
Turbine Fuel Consumption @ specified site conditions (LHV):	47.0 MMBtu/hr
KW Gross Output @ specified site conditions:	3,916 kW
Condensate Pump Power:	1.4 kW
Boiler Feed Pump Power:	15.2 kW
Total Auxiliary Power Consumption:	27 kW
Net Gas Turbine Power Production:	3,889 kW
Black Start kW Requirement (Turbine Generator Set Only)	200 kW
Boiler:	
Condensate Return:	60 %
Condensate Temperature:	212 °F
Makeup Water Temperature:	70 °F
Process Steam Pressure:	175.0 psig
Process Steam Temperature:	377 °F
Steam Contributed by Gas Turbine:	21,094 lbm/hr

Off-Design Performance

Solar Centaur

CENTAUR 50 T6200S
Natural Gas

Site Elevation:	3,209	feet
Barometric Pressure:	26.57	"Hg
Inlet Duct Loss:	4.0	"H2O
Exhaust Duct Loss:	10.0	"H2O

	CHP Off Design Incl Ductburner	
# of Turbines in Service	1	
Process Steam Demand	40,315	lbm/hr
Unfired Steam Flow	21,169	lbm/hr
Max Steam Flow	40,259	lbm/hr
Firing Temperature	1,435	°F
Duct Burner Fuel Flow	18.4	MMBtu/hr
Relative Humidity	60	%

Ambient Temperature (T1):	59.0	23.0	34.0	44.0	72.0	64.0	°F
Part Power (kWe), % Load, or 0 for Max	0	0	0	0	0	0.0	kWe
Engine Inlet Air Temperature (T1):	59.0	23.0	34.0	44.0	72.0	64.0	°F
Nominal Output Power @ Terminals:	3,916	4,364	4,232	4,116	3,715	3,980	kWe
Fuel Flow (LHV)	47.0	51.3	50.0	48.9	45.2	47.6	MMBtu/hr
Inlet Air Flow:	130,677	139,697	137,332	135,013	126,499	132,092	lbm/hr
Exhaust Gas Temperature (T7):	959	942	942	946	967	955	°F
Exhaust Gas Mass Flow:	132,956	142,187	139,760	137,384	128,692	134,400	lbm/hr
Exhaust Gas Volumetric Flow:	33,856	36,228	35,601	34,990	32,764	34,203	SCFM
Nominal Electrical Efficiency @ Terminals	28.5	29.0	28.9	28.8	28.1	28.5	%
Nominal Electrical Heat Rate @ Terminals	11,994	11,766	11,820	11,871	12,165	11,966	Btu/kWHR
Exhaust Heat Captured:	24.6	26.7	26.2	24.9	24.1	24.7	MMBtu/hr
% Argon, wet:	0.9	0.9	0.9	0.9	0.9	0.9	
% CO_2, wet:	3.0	3.1	3.0	3.0	3.0	3.0	
% H_2O, wet:	6.4	6.6	6.5	6.6	6.4	6.3	
% N_2, wet:	75.3	75.3	75.3	75.3	75.3	75.4	
% Oxygen, wet:	14.4	14.2	14.3	14.3	14.4	14.4	
					Net CHP System Efficiency =	86.1	% (LHV)

Off-Design Performance

Solar Mercury Recuperated Gas Turbine

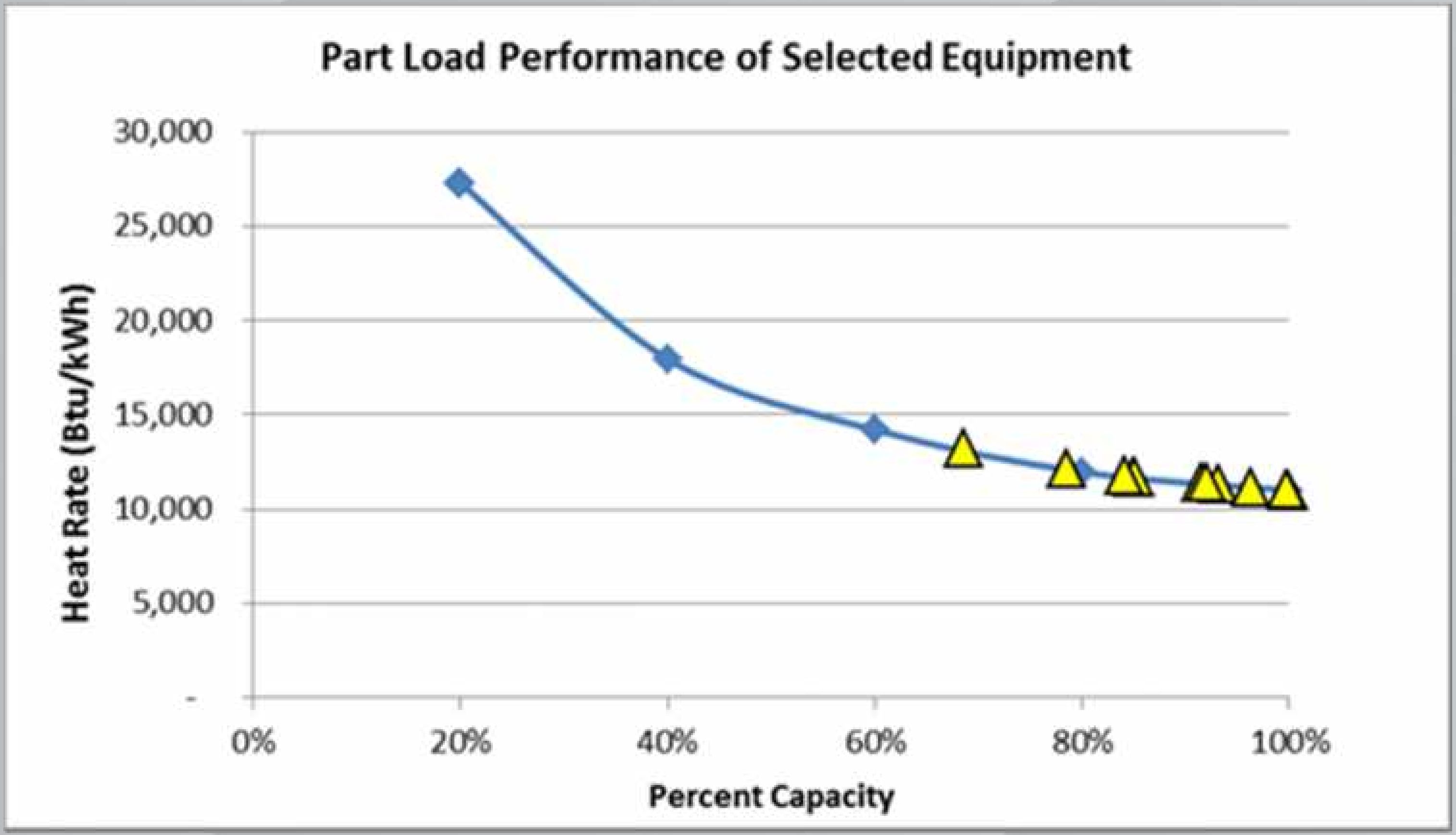
MERCURY 50-6400R
Natural Gas

CHP Off Design	Incl Ductburner	
# of Turbines in Service	1	
Process Steam Demand	40,315	lbm/hr
Unfired Steam Flow	10,114	lbm/hr
Max Steam Flow	40,227	lbm/hr
Firing Temperature	1,509	°F
Duct Burner Fuel Flow	29.1	MMBtu/hr
Relative Humidity	60	%

Site Elevation:	3,209	feet
Barometric Pressure:	26.57	"Hg
Inlet Duct Loss:	4.0	"H2O
Exhaust Duct Loss:	7.0	"H2O

						CHP Off Design (Incl Ductburner)	
Ambient Temperature (T1):	59.0	23.0	34.0	44.0	72.0	54.0	°F
Part Power (kWe), % Load, or 0 for Max	0	0	0	0	0	0.0	kWe
Engine Inlet Air Temperature (T1):	59.0	23.0	34.0	44.0	72.0	54.0	°F
Nominal Output Power @ Terminals:	3,941	4,497	4,368	4,188	3,712	4,021	kWe
Fuel Flow (LHV)	35.8	38.9	38.5	37.4	34.4	36.3	MMBtu/hr
Inlet Air Flow:	122,458	131,088	130,120	126,973	118,389	123,938	lbm/hr
Exhaust Gas Temperature (T7):	696	663	669	679	708	690	°F
Exhaust Gas Mass Flow:	124,196	132,977	131,990	128,786	120,066	126,699	lbm/hr
Exhaust Gas Volumetric Flow:	31,462	33,698	33,446	32,629	30,408	31,823	SCFM
Nominal Electrical Efficiency @ Terminals	37.6	39.4	38.7	38.3	36.9	37.8	%
Nominal Electrical Heat Rate @ Terminals	9,083	8,655	8,818	8,919	9,254	9,030	Btu/kWHR
Exhaust Heat Captured:	14.2	13.7	14.2	14.2	14.1	14.2	MMBtu/hr
% Argon, wet:	0.9	0.9	0.9	0.9	0.9	0.9	
% CO_2, wet:	2.4	2.6	2.6	2.6	2.4	2.6	
% H_2O, wet:	5.4	5.5	5.4	5.4	5.4	5.3	
% N_2, wet:	75.7	75.7	75.7	75.7	75.7	75.8	
% Oxygen, wet:	15.5	15.5	15.5	15.5	15.6	15.6	
					Net CHP System Efficiency =	86.8	% (LHV)

Part-Load Efficiency



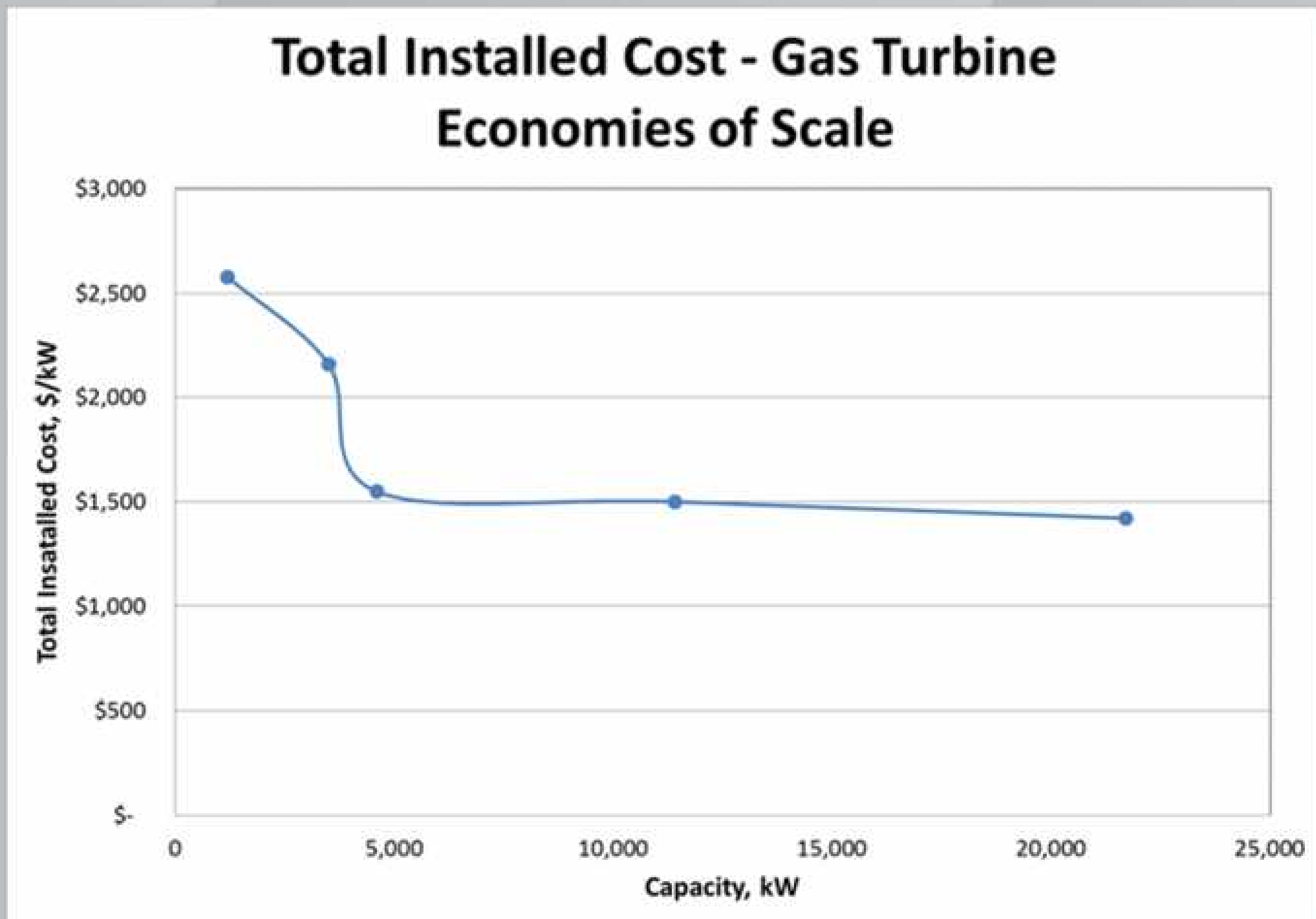
Temperature, elevation, and part load affect performance/cost

Economies of Scale

- Total installed cost, $/kW
- Heat rate, Btu/kWh
- Transport gas availability and cost

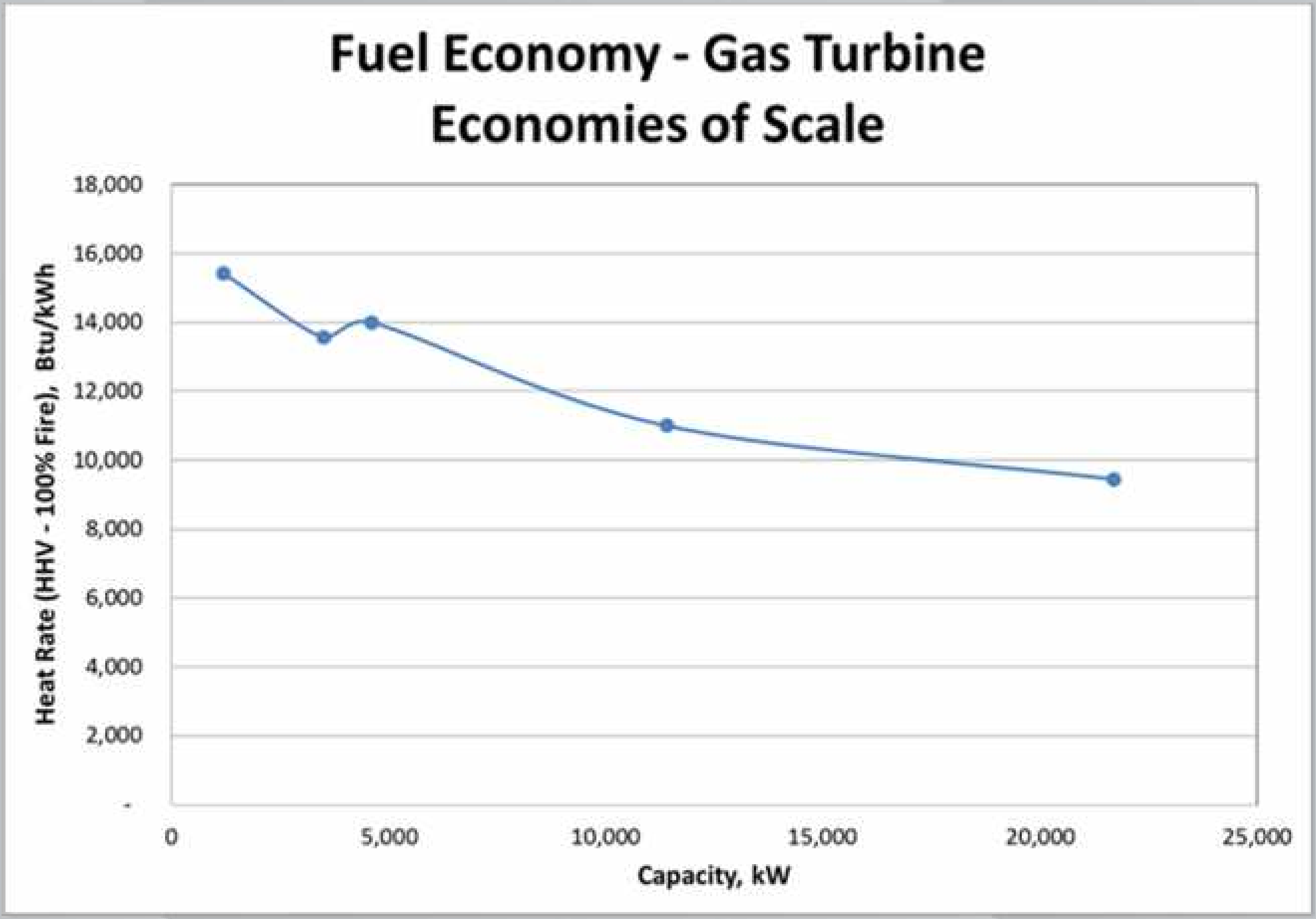
Economies of Scale

Gas Turbine Costs



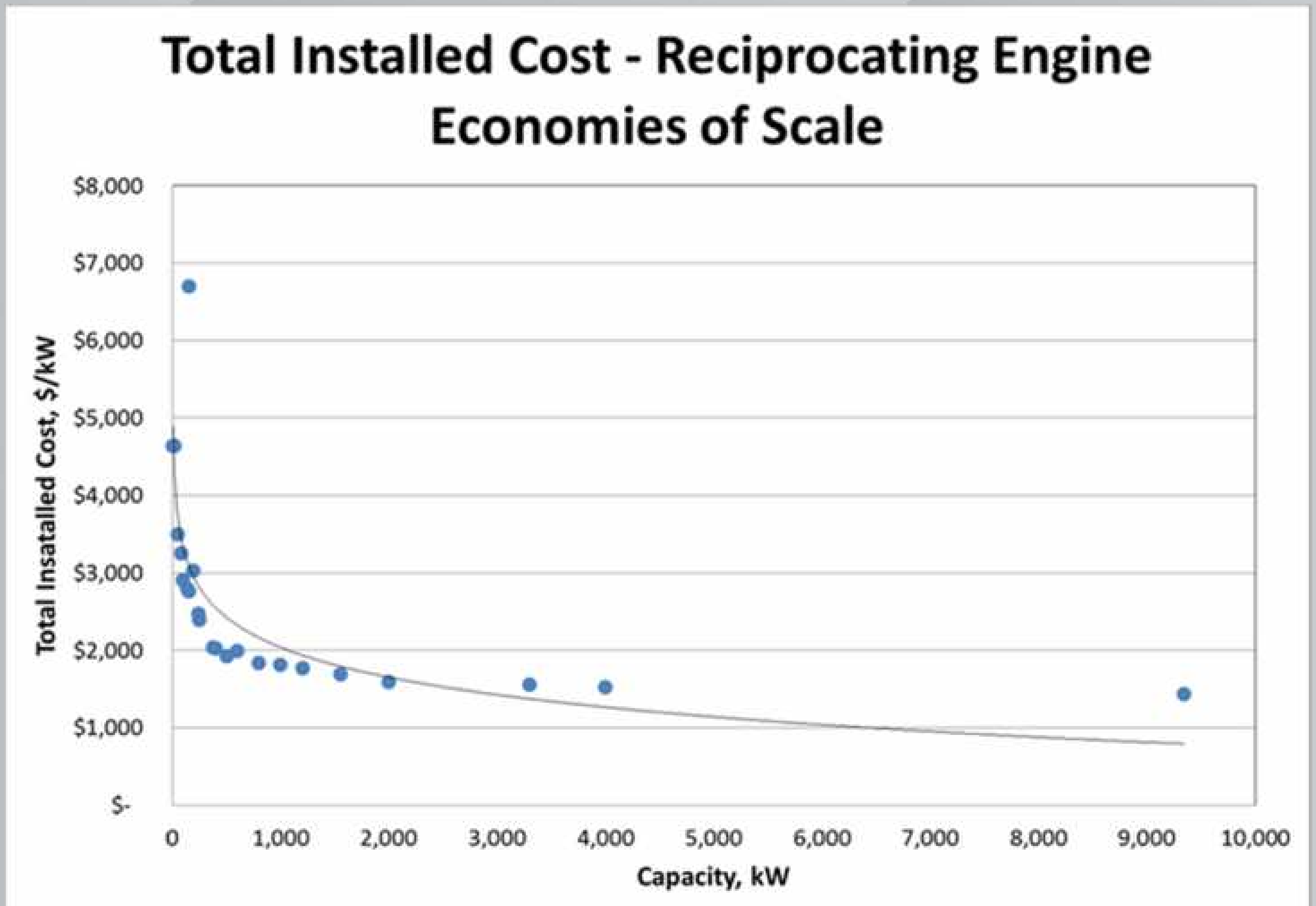
Heat Rates

Full Fire vs. Gas Turbine Rating



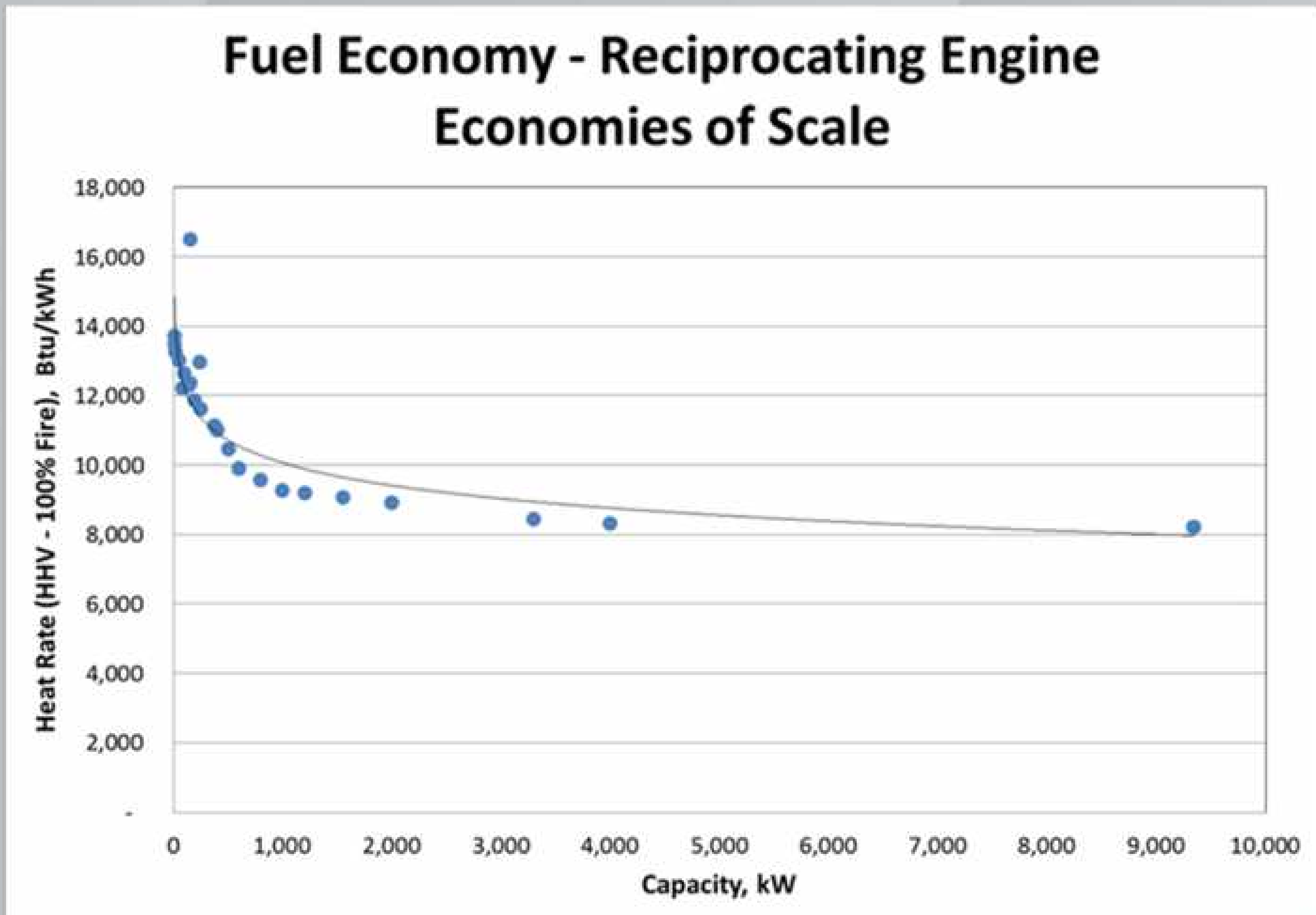
Economies of Scale

Reciprocating Engine Gensets



Heat Rate

Rated Capacity vs. Power Rating



Cost Estimate for CHP Project Example

Gas Turbine Equipment		
(1) Natural Gas Fuel, Mercury 50 SoLoNOx Turbine Generator Set		$4,500,000
Commissioning Parts, Startup, and Site Testing		$191,500
Electrical Equipment		
No Additional Electrical Equipment Included		
Mechanical Equipment		
1 Heat Recovery Steam Generator with ductburners	$1,524,000	
HRSG Options	none selected	
Total for Heat Recovery Steam System		$1,524,000
Miscellaneous		
Construction Estimate		by others
Project Management & Engineering (Loose Ship Equipment Only)		$106,600
Shipping		$93,300
0% Balance of Plant Contingency		$0
Total for BOP Equipment (installation not included)		$1,723,400
Grand Total for Turbomachinery and Balance of Plant		**$6,414,900**
Estimation of cost per ISO rating kilowatt for selected equipment		$1,394
FSA Cost per Month (Only Turbomachinery Covered)		$60,360

Steam Consumption

Average Monthly by Hour

Monthly Averages by Hour

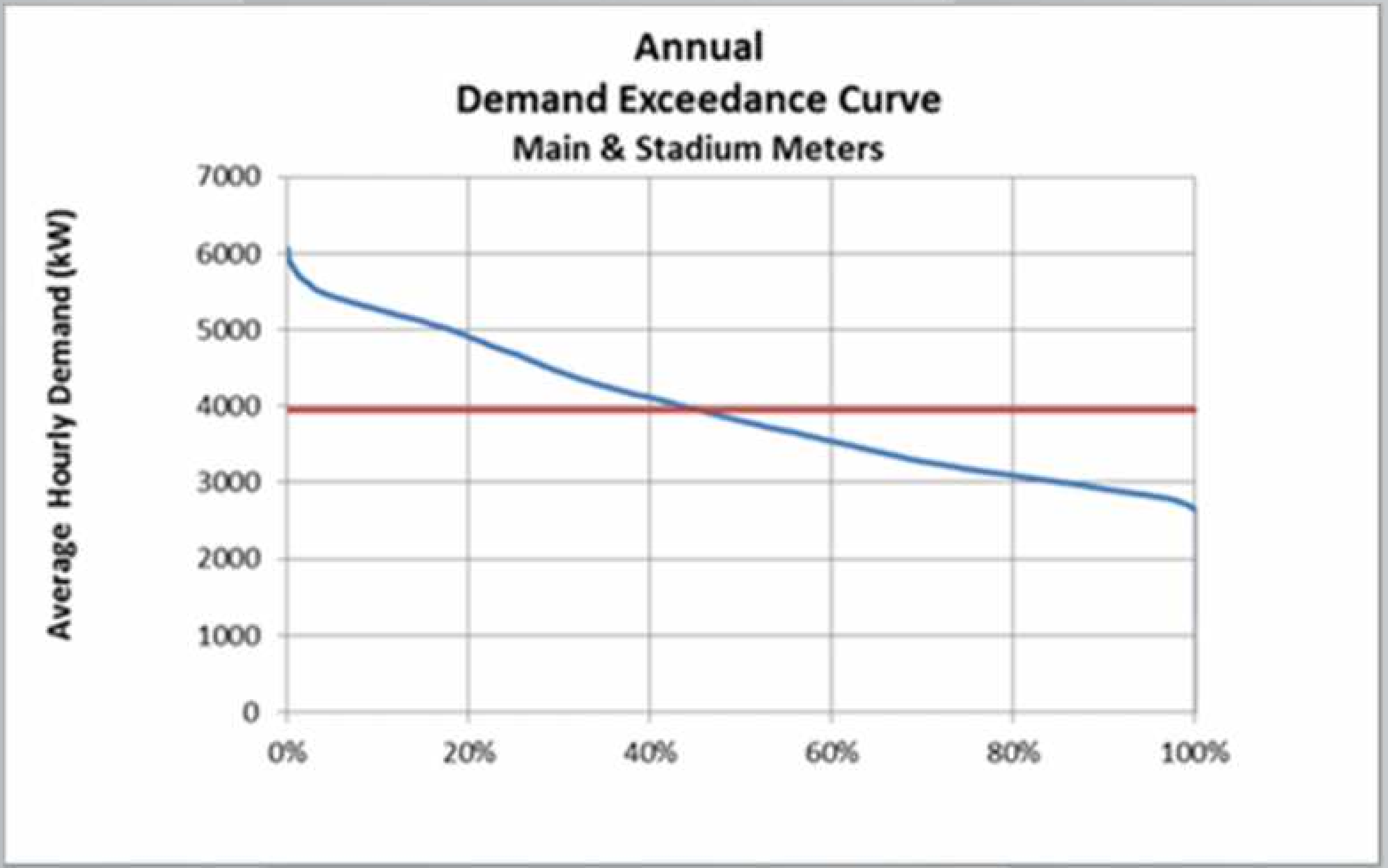
Row Labels	Average of Midnight	Average of 3:00 AM	Average of 6:00 AM	Average of 9:00 AM	Average of Noon	Average of 3:00 PM	Average of 6:00 PM	Average of 9:00 PM
⊟Jan								
⊞Weekday	27,330	27,858	29,129	29,437	27,992	26,362	27,535	27,463
⊞Weekend	26,746	26,916	28,129	28,150	26,680	24,772	25,424	26,089
⊞Feb	23,427	23,655	26,228	28,323	24,878	22,069	23,282	24,356
⊞Mar	19,382	19,974	23,092	26,377	21,173	17,408	17,433	18,680
⊞Apr	16,222	17,171	19,501	22,588	17,646	14,860	14,649	15,285
⊞May	10,873	11,645	14,141	15,543	12,141	10,756	10,309	10,724
⊞Jun	7,231	7,629	8,635	8,799	8,195	7,580	7,248	6,908
⊞Jul	6,719	6,868	7,741	8,247	7,543	7,111	7,019	6,645
⊞Aug	6,827	6,886	7,830	8,376	7,914	7,202	6,920	6,694
⊞Sep	9,346	8,846	10,567	14,085	10,788	9,552	9,304	9,739
⊞Oct	12,948	12,579	14,983	19,141	15,199	12,324	12,070	13,164
⊞Nov	21,903	21,429	23,668	26,743	24,003	21,855	23,347	22,862
⊞Dec	26,309	26,327	27,684	28,760	28,527	27,328	27,680	27,382
Overall Average	15,761	15,936	17,776	19,708	17,204	15,383	15,588	15,871

Seasonality of Steam Generation

Monthly Averages by Day and Hour

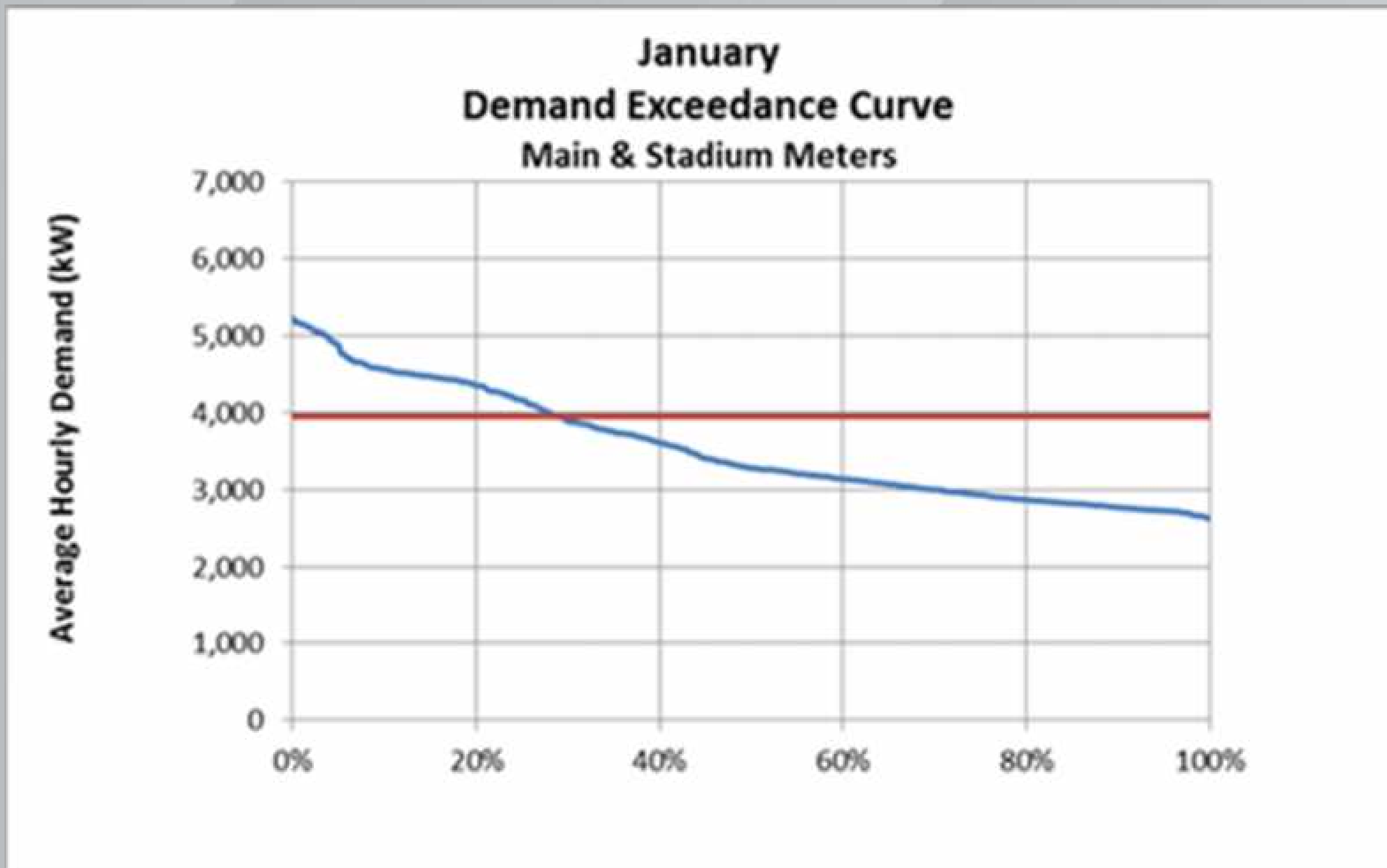
Row Labels	Average of Midnight	Average of 3:00 AM	Average of 6:00 AM	Average of 9:00 AM	Average of Noon	Average of 3:00 PM	Average of 6:00 PM	Average of 9:00 PM
Jan								
Weekday	**27,330**	**27,858**	**29,129**	**29,437**	**27,992**	**26,362**	**27,535**	**27,463**
Monday	25,588	26,346	27,927	28,916	26,850	25,464	26,857	26,554
Tuesday	25,146	27,068	29,362	29,661	26,144	23,937	26,725	25,530
Wednesday	25,723	26,928	29,572	29,538	27,369	25,838	27,289	28,816
Thursday	29,558	29,663	29,501	29,500	29,600	28,768	29,367	29,357
Friday	29,196	29,354	29,690	29,516	29,128	26,685	27,508	26,948
Tuesday	26,800	23,500	26,800	29,739	26,889	25,690	24,645	24,594
Weekend	**26,746**	**26,916**	**28,129**	**28,150**	**26,680**	**24,772**	**25,424**	**26,089**
Sunday	26,606	26,597	27,118	27,735	25,357	23,237	24,846	24,474
Saturday	26,857	27,171	28,938	28,482	27,739	26,000	25,886	27,380
Jul								
Weekday	**6,759**	**7,002**	**8,046**	**8,613**	**7,788**	**7,298**	**7,154**	**6,732**
Monday	6,630	7,291	7,413	8,746	8,459	7,701	7,673	7,034
Tuesday	7,107	7,213	7,911	8,814	8,133	7,172	7,198	7,023
Wednesday	6,568	6,953	8,198	8,370	7,601	7,531	7,533	6,418
Thursday	6,936	6,924	8,362	8,597	7,396	6,951	7,301	6,277
Friday	6,600	6,730	8,193	8,606	7,554	7,191	6,178	7,026
Weekend	**6,603**	**6,481**	**6,866**	**7,192**	**6,840**	**6,573**	**6,631**	**6,396**
Sunday	6,565	6,320	6,688	7,217	6,996	6,754	7,165	6,543
Saturday	6,642	6,642	7,043	7,168	6,683	6,392	6,097	6,248

Exceedance Curve for Electrical Energy Purchases



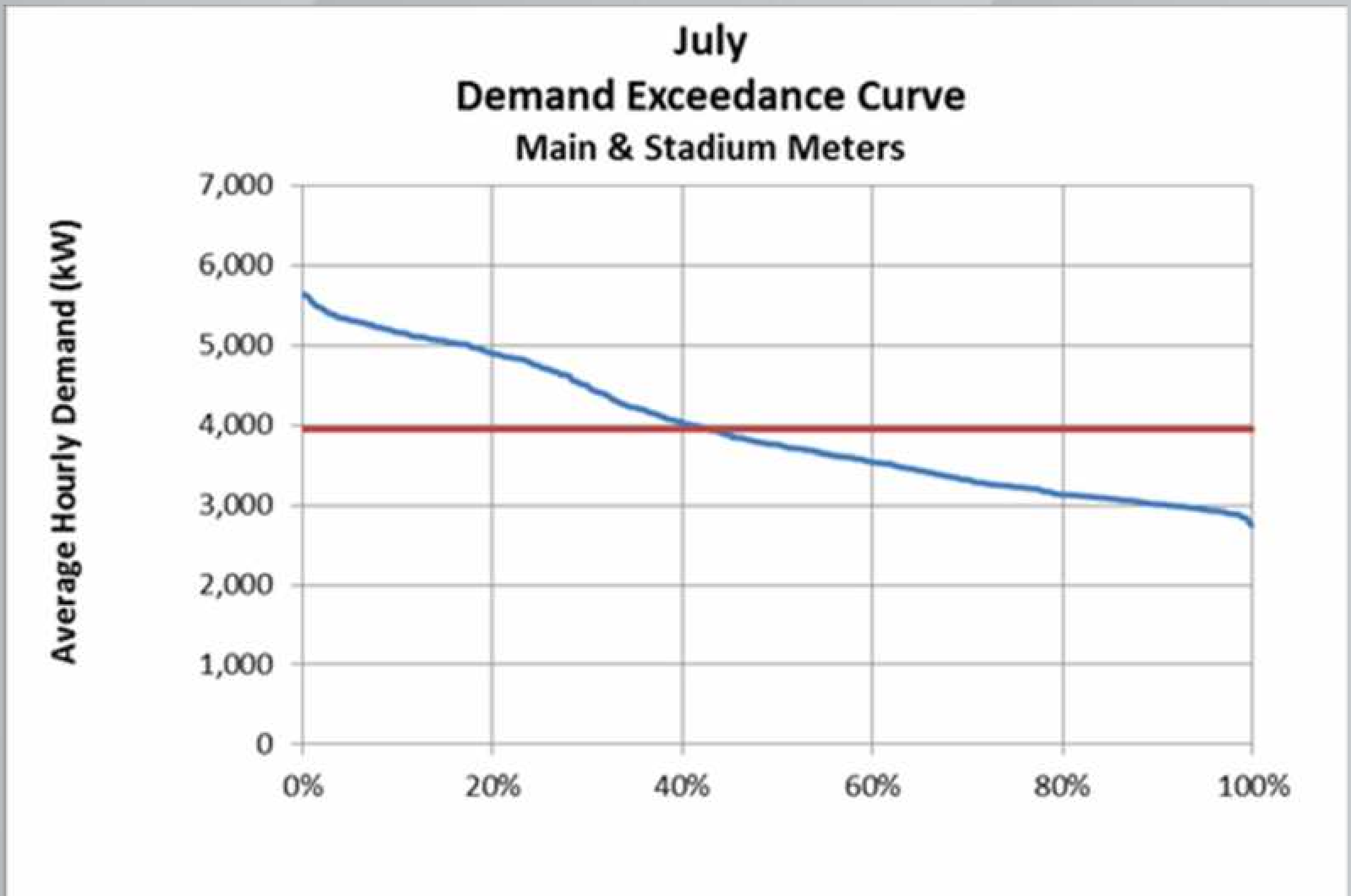
Exceedance Curve

Electrical Consumption – January



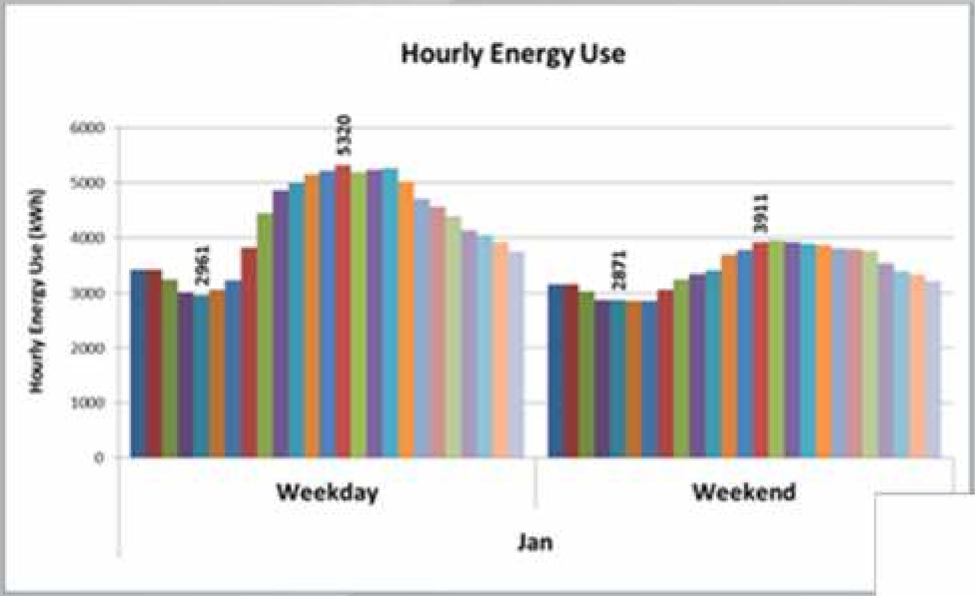
Exceedance Curve

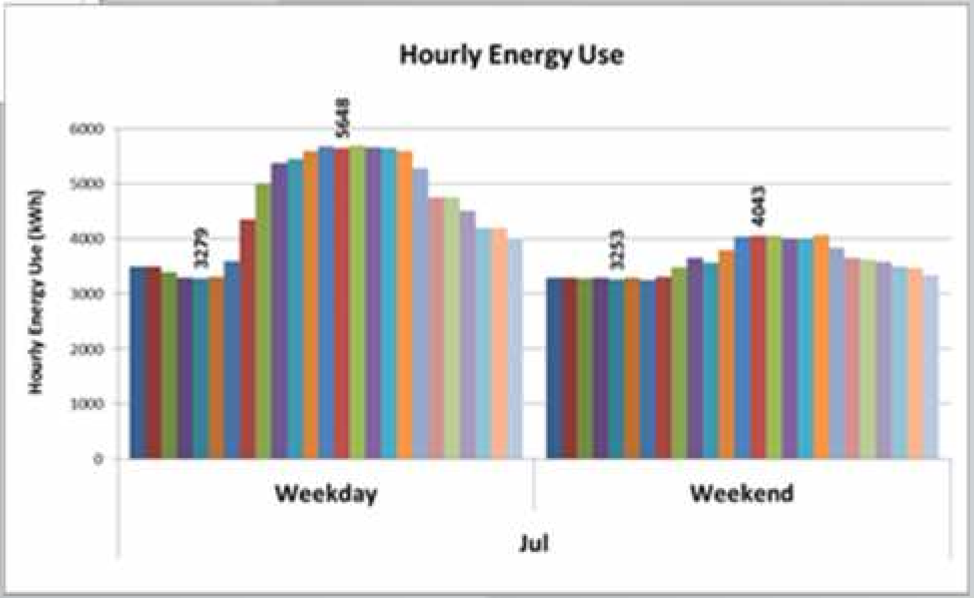
Electrical Consumption – July



Hourly Average Electrical Energy Use

Seasonality Comparison





Assessment Tools

- CHP System Selection Analysis
- Steam Turbine Monthly Analysis
- Greenhouse Gas (GHG) Emissions Analysis
- RelCost Financial Analysis

Washington State University Energy Program

Go Cougs!

Thank You!
Questions?

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360-956-2144 karrm@energy.wsu.edu

David Sjoding, Director
360-956-2004 sjodingd@energy.wsu.edu

Emissions Reduction Calculators

CHP Results

CHP
EPA COMBINED HEAT AND POWER PARTNERSHIP

The results generated by the CHP Emissions Calculator are intended for eductional and outreach purposes only; it is not designed for use in developing emission inventories or preparing air permit applications.

Annual Emissions Analysis					
	CHP System	Displaced Electricity Production	Displaced Thermal Production	Emissions/Fuel Reduction	Percent Reduction
NOx (tons/year)	43.74	22.83	59.06	38.15	47%
SO2 (tons/year)	0.02	53.95	1.53	55.46	100%
CO2 (metric tons/year)	67,226	22,818	63,514	19,107	22%
Carbon (metric tons/year)	18,334	6,223	17,322	5,211	22%
Fuel Consumption (MMBtu/year) (HHV)	1,250,232	280,394	1,181,209	211,372	14%
Acres of Forest Equivalent				5,211	
Number of Cars Removed				3,257	

This reduction is equal to removing the carbon emissions of 3,257 cars

Steam Turbine Calculator

U.S. DOE Office of Energy Efficiency and Renewable Energy

Two common methods for using the Steam Turbine Calculator

- Calculate steam turbine (generator) power, given:
  - Inlet pressure
  - Inlet temperature
  - Steam flow
  - Exhaust pressure

  This is the most typical method when calculating ST output

- Calculate steam flow, given:
  - Inlet pressure
  - Inlet temperature
  - Exhaust pressure
  - Desired power (kWe)

Backpressure Turbine

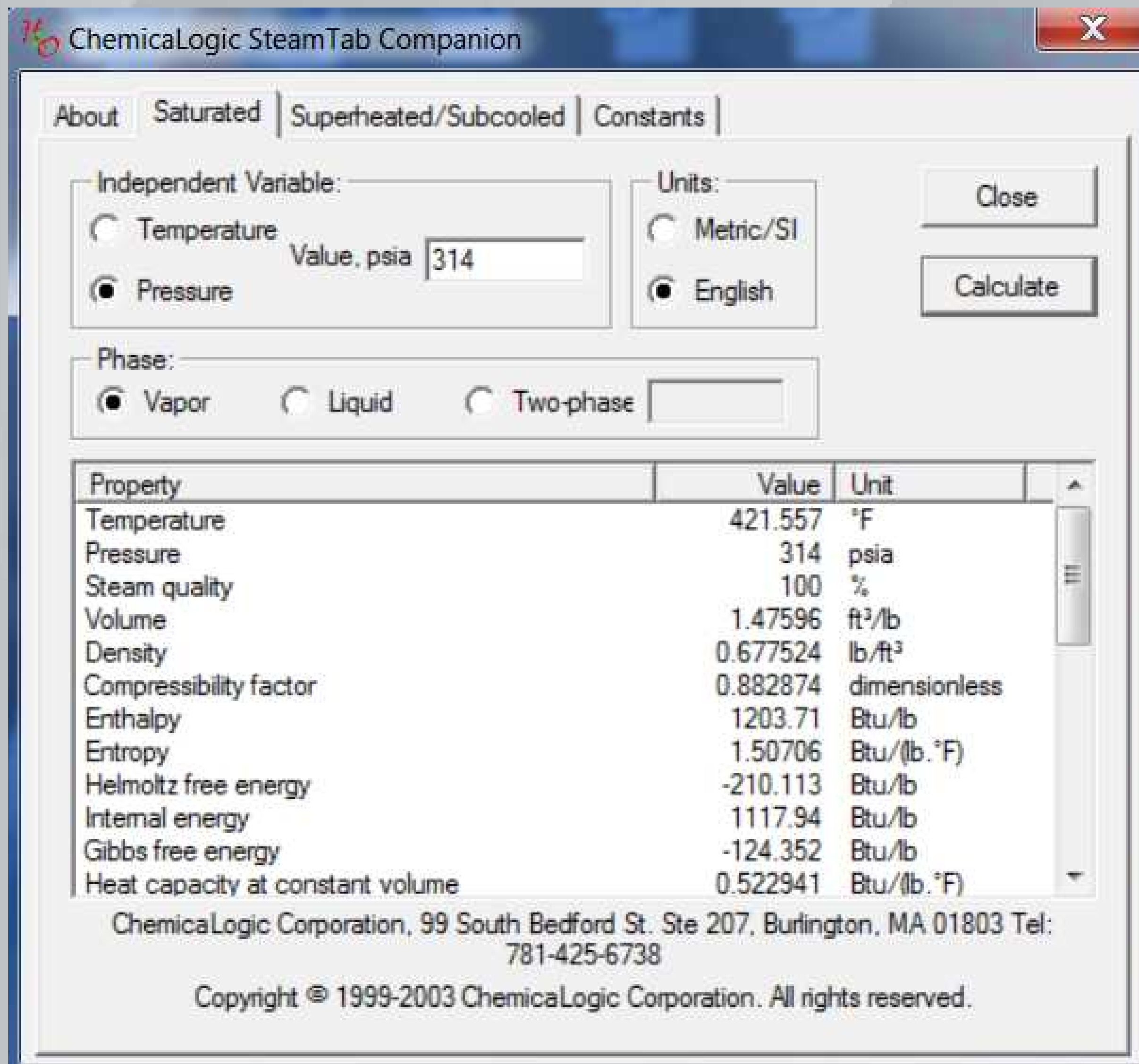
Isentropic Efficiency Defaults

Table 2: Estimated Isentropic Efficiencies of Steam Turbines

Turbine Type	Exhaust Type	Average (%)
Single Stage	Back Pressure	53
Single Stage	Condensing	57
Multi-Stage <10 MW	BackPressure	60
Multi-Stage <10 MW	Condensing	67
Multi-Stage > 10 MW	Back Pressure	75
Multi-Stage > 10 MW	Condensing	80

Note: Isentropic efficiencies of Steam Turbines can range from 20-90%. The efficiencies in Table 1 are simplified values for the purpose of estimating industrial type Steam Turbine Generators. For firm performance values please contact the Power Generation Team at Elliott Group.

Steam Properties Calculator



Boiler Combustion Efficiency Calculator

U.S. DOE Steam System Assessment Tool (SSAT)

Steam System Assessment Tool

Stack Loss Calculator

Based on user inputs of Stack Temperature, Ambient Temperature and Stack Oxygen Content, an estimate will be provided of the heat loss from the boiler stack. Losses are expressed as a percentage of the heat fired.

Stack losses are related to SSAT Boiler Efficiency as follows:

SSAT Boiler Efficiency = 100% - Stack Loss (%) - Shell Loss (%)

Shell Loss refers to the radiant heat loss from the boiler. Typically <1% at full load, 1-2% at reduced load.

Input Data

Stack Gas Temperature (°F)	400 °F	Stack Temperature - Ambient Temperature = 330°F
Ambient Temperature (°F)	70 °F	

Stack Gas Oxygen Content (%)	5 %	

Note: Stack gas oxygen content is expressed on a molar or volumetric basis

Results

Estimated Stack Losses for each of the default fuels are as follows:

Natural Gas	**18.5 %**
Number 2 Fuel Oil	**14.1 %**
Number 6 Fuel Oil (Low Sulfur)	**13.7 %**
Number 6 Fuel Oil (High Sulfur)	**13.9 %**
Typical Eastern Coal (Bituminous)	**12.2 %**
Typical Western Coal (Subbituminous)	**13.8 %**
Typical Green Wood	**24.9 %**

Boiler Replacement Choices

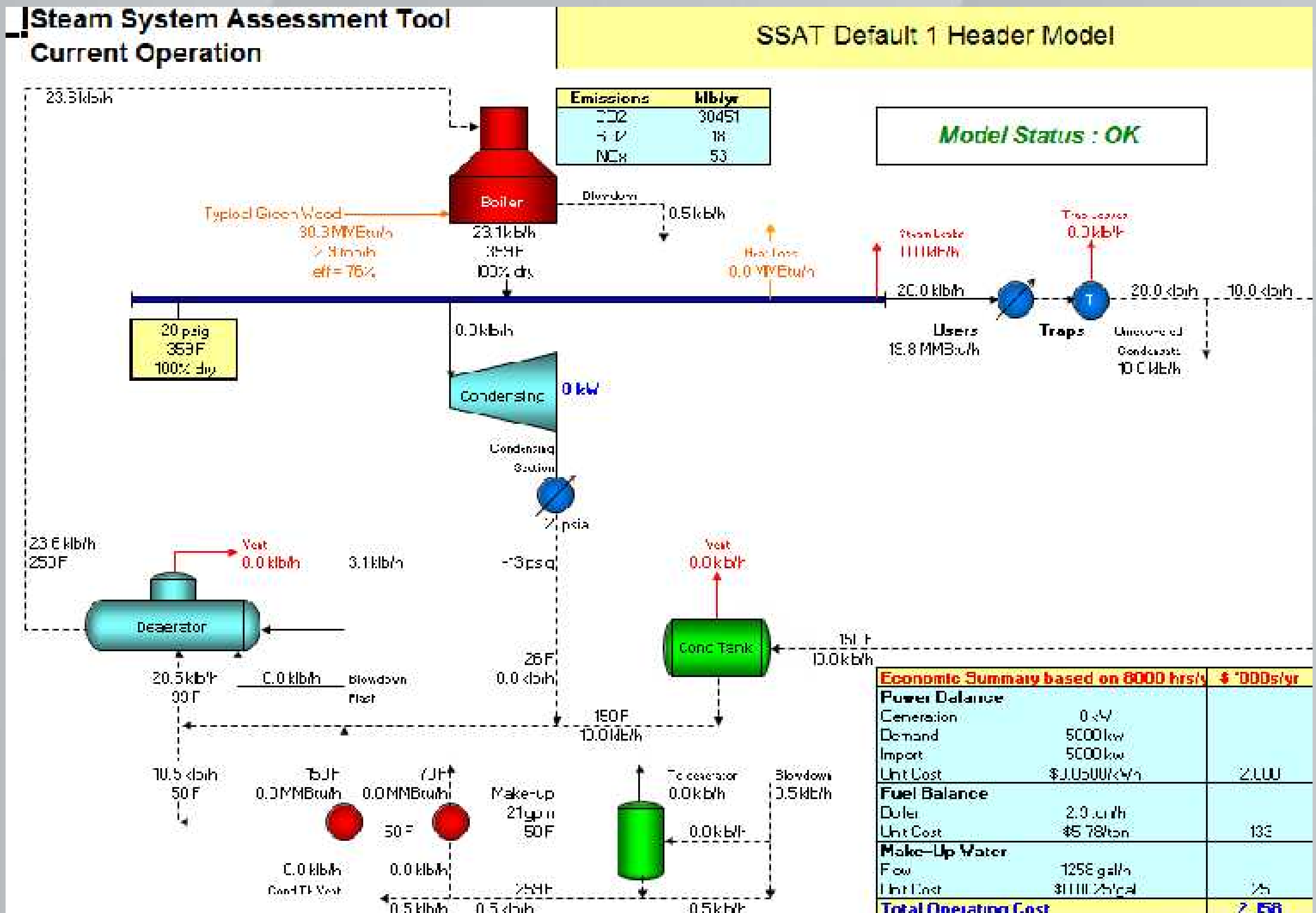
- When nearing end-of-life, consider a new boiler of the same steam output and pressure (this is your baseline cost).
- Consider a new MP (300-psig) saturated steam boiler with a backpressure turbine between a MP header and the LP header.
- Consider a 600-psig HP boiler delivering 750°F saturated steam to justify a boiler size increase, possibly with a condensing and backpressure turbine (or condensing/extraction unit).
- Consider a gas turbine with a HRSG if natural gas is available

Appropriate Boiler Pressures

- Packaged fire tube boilers and smaller water tube boilers (<35,000 lbs/hour of steam) are generally limited to providing saturated steam at a pressure of 300-psig or less. Steam quality is reduced if routed through a backpressure turbine.
- Larger boilers can include super-heaters and provide steam at 600-psig/750^{o}F (this is somewhat of an industry standard rating).

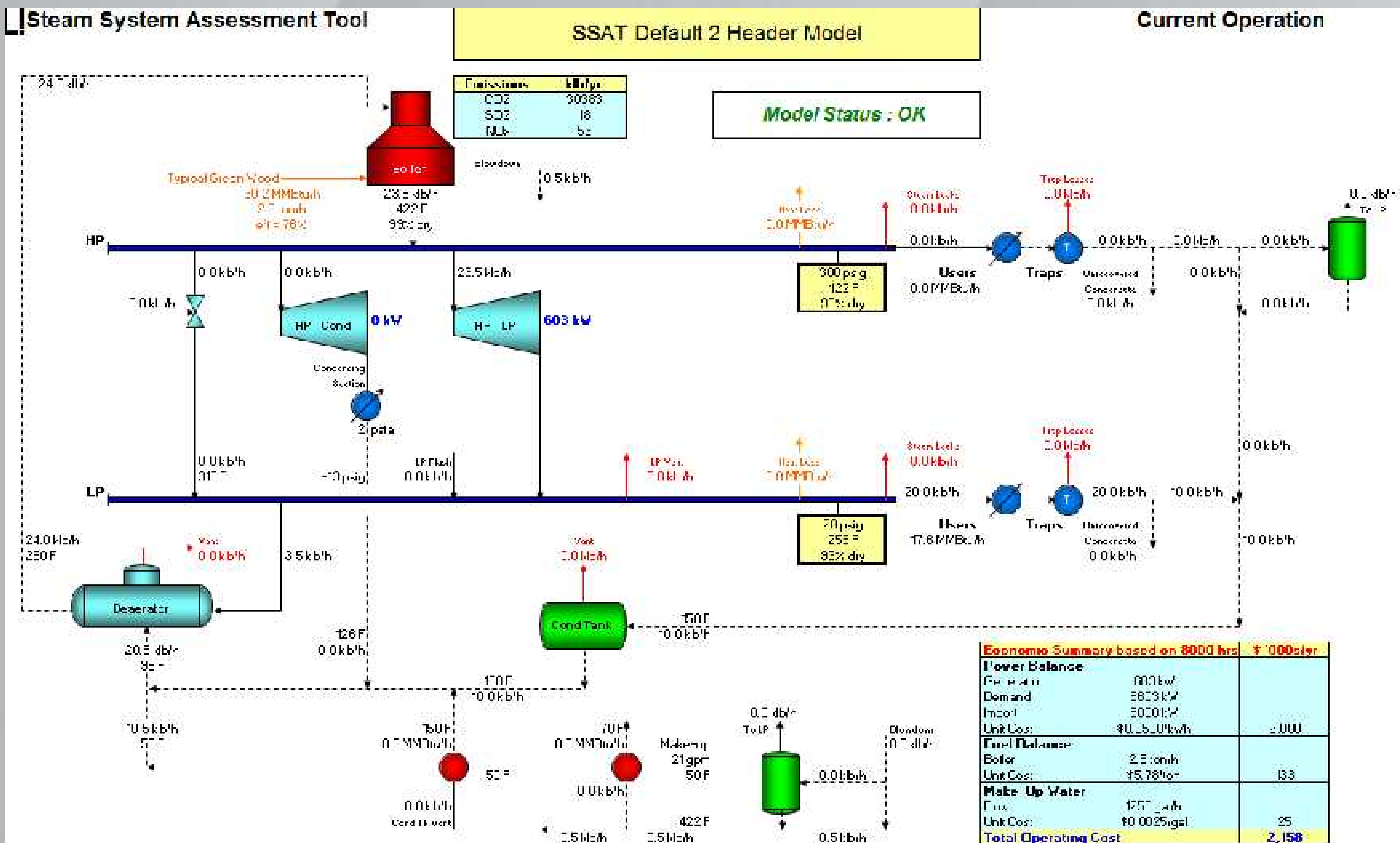
Baseline System

Biomass if Natural Gas is Not Available



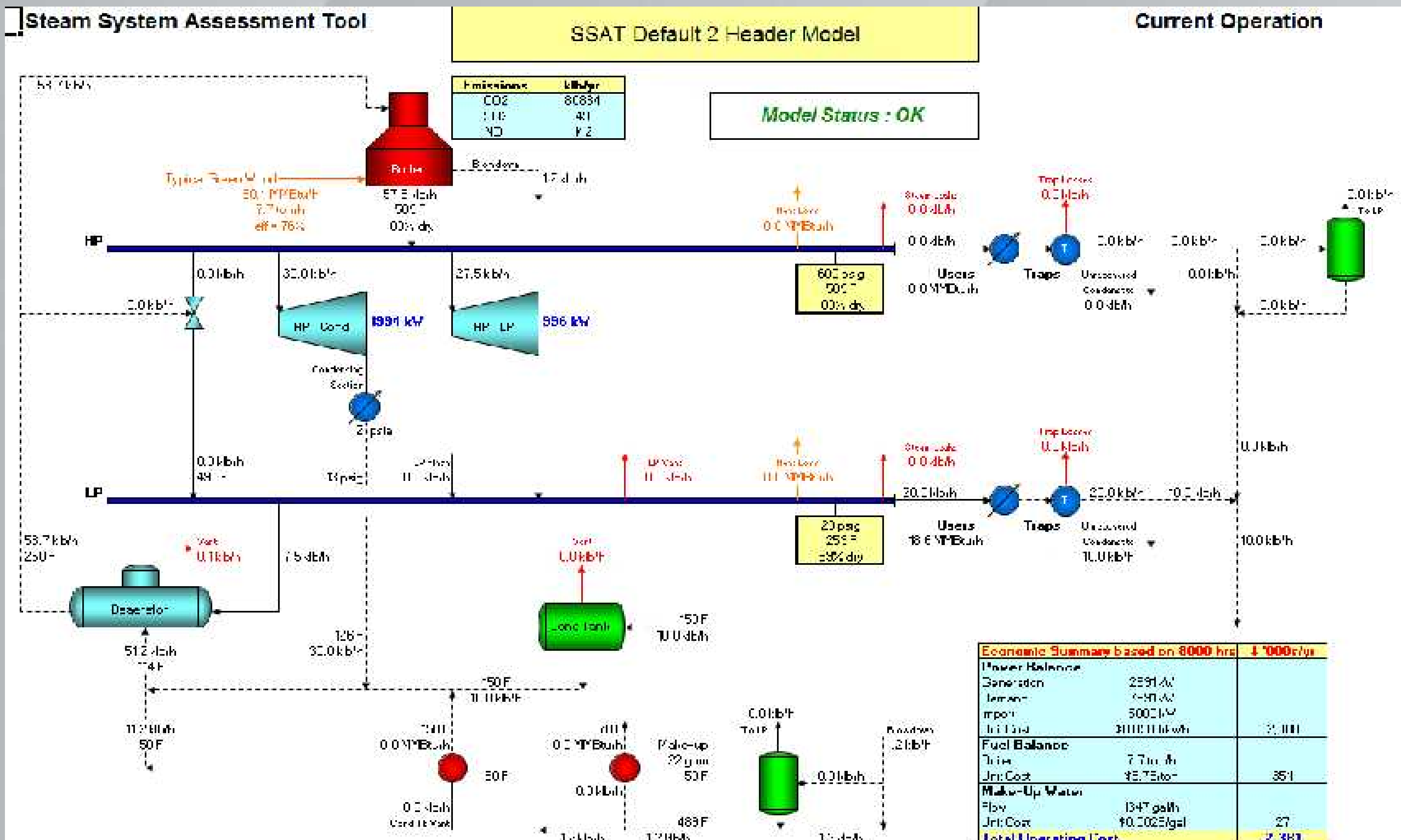
Replacement MP Boiler

300-psig Saturated



New HP Boiler

600-psig/750ºF Superheated Steam



Design Considerations

- Routing saturated steam through a backpressure turbine results in low-quality steam delivered to the LP header. Provide additional steam traps to remove the additional moisture.
- Optimize the steam system to reduce steam loads (such as increased condensate return).
- Additional fuel is required to account for the energy contained in the generated electricity.
- Use an appropriate turbine isentropic efficiency.

Fuel Consumption Adjustment

- The additional fuel consumption is the electrical energy produced by the backpressure turbine multiplied by 3,413 Btu/kWh, divided by the boiler and generator efficiencies (76% and 96%, respectively).
- Backpressure turbines produce electrical energy at close to the boiler efficiency.
- Wood-fired boilers have full-load efficiencies between 69% and 76%, depending on wood species and moisture content.

Common Mistakes in CHP Assessments

- Placing all the system costs on the electricity side and none on the thermal side. Then, when comparing project costs on a per kWh basis to the electric utility kWh costs, finding that "It doesn't pencil out."
- Assuming CHP is not applicable to building types, like a school.
- Under-sizing the feed-auger in a biomass CHP, shortchanging the power available.
- Failing to understand equipment performance; the main thermal need can be hot water or steam.
- Recognizing that gas turbine firing rates are in terms of lower heating value.
- Not considering appropriate gas and steam turbine part-load efficiency values.
- Not considering on-site CHP-related electrical energy consumption (service loads).

Common Mistakes in CHP Assessments
(continued)

- Not using availability factors and O&M costs that are realistic and technology appropriate.
- Ignoring the game changing nature of fracking for future natural gas pricing.
- Not doing a detailed and site-specific CHP analysis.
  - Oregon alone has 41 retail electrical utilities with varying electrical rates, purchase prices, and hookup requirements.
- Lack of experience in doing a true feasibility study. There is no CHP certification.
- Incomplete feasibility study with no recommended size of system (0 to 8 MW range).
- Gold plating (i.e., overpricing the system).